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Determination of Turbulent Velocities by Nonlinear Acoustic
Scattering



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**Determination of Turbulent Velocities by Nonlinear Acoustic
Scattering**

A Trident Scholar Project Report

by

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ABSTRACT

The scattering of sound by the nonlinear interaction of two sound beams in the presence of turbulence is used to experimentally measure the turbulent velocities generated by a submerged water jet. When two sound beams of primary frequencies f_{01} and f_{02} intersect in a region of turbulent flow, the nonlinear scattering generates sum and difference frequency components ($f_{0+} = f_{01} + f_{02}$ and $f_{0-} = f_{01} - f_{02}$) which radiate outside the interaction region. In the absence of turbulence, the crossed beams do not produce radiated sum and difference frequencies. In this experiment, two transducers emit continuous wave focused sound beams of frequencies $f_{01} = 2.0$ MHz and $f_{02} = 2.1$ MHz, respectively. The sound beams are arranged so that their focal points overlap and the beam axes are mutually perpendicular. A receiving transducer, located outside the interaction region, detects the scattered sum frequency ($f_{0+} = 4.1$ MHz).

The turbulent velocities in the small interaction volume are determined from variations in the shape of the scattered sum frequency's intensity spectrum that are measured at each scattering angle. The motion of the turbulent eddies (which are responsible for the nonlinear scattering) generates a random Doppler shift of the sum frequency component which broadens its intensity spectrum. Measurements of the average Doppler shift, rms frequency, skewness, and kurtosis of the time averaged spectra are used to correlate the mean and turbulent velocity components along the radial and axial directions of the jet. Scattering results measured at 80 angles for each of 11 scan positions across the jet are used to map out the velocity correlation coefficients of the turbulence. Results are then compared with earlier published experiments that use conventional hot wire probes to measure a similar turbulent jet flow in air.

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HISTORICAL INTRODUCTION

This underwater experiment studies a nonlinear acoustic scattering phenomenon which generates sum and difference frequencies as a result of the scattering of sound by sound in the presence of turbulence. It is well known that when two collinear finite-amplitude sound beams of different frequencies interact, they produce two new frequencies which are equal to the algebraic sum and difference of the original two frequencies. These are commonly referred to as "combination" frequencies. When these same two sound beams (each considered to be well collimated) interact at right angles to each other, the combination frequencies are again created but do not radiate beyond the bounds of the region defined by the overlap of the two sound beams¹. Fig. 1 graphically describes the overlap region.

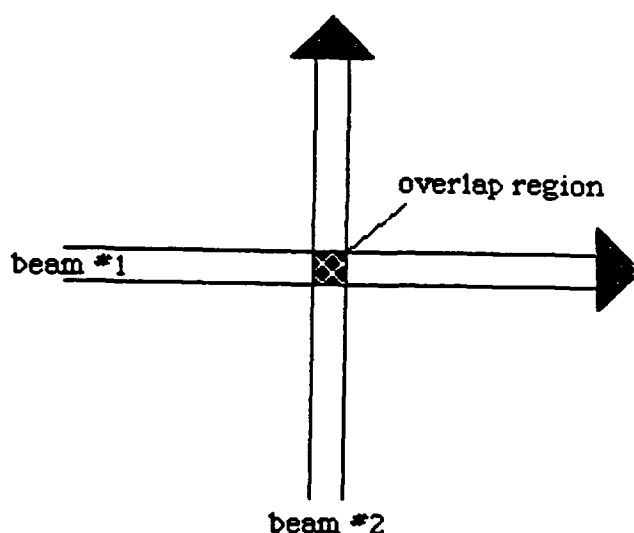


FIG. 1. Region defined by overlapping sound beams

In order to produce a situation where the sum and difference frequencies can radiate outside the overlap region (of the

crossed beams), one must introduce a solid object, air bubbles, inhomogeneous medium, or a turbulent flow in the interaction region^{10,11}. In these cases, the nonlinear interaction will allow sum and difference frequency components to radiate.

The intent of this paper is to explore the nonlinear scattered sum frequency component when turbulence is present in the interaction region of the crossed sound beams.[§] Experimental measurements of the characteristic properties of the sum frequency component's intensity spectrum will be used to determine many statistical quantities associated with the turbulent velocity field.

In the early 1980s, Korman and Beyer^{4,5} developed an experiment to study the nonlinear scattering of crossed sound beams in the presence of turbulence. Their experimental apparatus generated mutually perpendicular acoustic beams (each with half power beam widths of about 1 degree) from two unfocused circular plane array transducers. A submerged circular water jet created the turbulence in their water tank. With this apparatus, they measured the intensity of the scattered sum frequency as a function of angle. To analyze the data, Korman and Beyer modeled the turbulence as an isotropic distribution of homogeneous randomly fluctuating velocities

§ Note that throughout this paper, extensive references are made to the sum frequency and very little is said about the difference frequency component. This is not an oversight. It is known that the relative intensity of the difference frequency component to the sum frequency component is very small. This makes detection of the difference frequency difficult. Since the wavelengths of the sum frequency are much smaller than the difference frequency, one can perform the experiments in a small laboratory tank. Further, an analysis of scattering at the difference frequency reveals that angular scattering is very insensitive to the characteristic length scales of the turbulence in contrast to scattering at the sum frequency.

superimposed upon a mean flow velocity. They modeled the turbulent velocity fluctuations to behave with Gaussian statistics. With this model, they could predict the average features of the turbulent flow across their jet from the shape of the scattered acoustic intensity spectra. Specifically, the Doppler shift, ω_d , of the sum frequency was related to the jet's mean velocity, V , and the spectral broadening was related to the rms turbulent flow velocity, σ . The intensity spectrum $I_+(f, \theta_*)$ integrated over all frequencies in a band near the sum

frequency component $I_+(\theta_*) = \int I_+(f, \theta_*) df$

was related to the turbulent kinetic energy spectrum, $E(k)$, which describes the wavenumber, k , of the turbulent eddies. Here, $I_+(\theta_*)$ is the total intensity at the scattering angle θ_* .

In 1987, Korman worked with Rife on a USNA Trident Project⁸ to measure turbulent velocities with focused sound beams. Focusing the beams minimized the volume of the interaction region and allowed Korman and Rife to spatially resolve the velocity information derived from the scattered spectra. This was not possible in Korman and Beyer's earlier work because the volumes defined by the overlapping beams were too large to resolve any details of the jet.

Korman and Rife^{6,7} performed two different acoustic scattering experiments with the focused ultrasonic beams. The first involved two crossed focused beams which were translated across the width of the jet, as shown in Fig. 2.

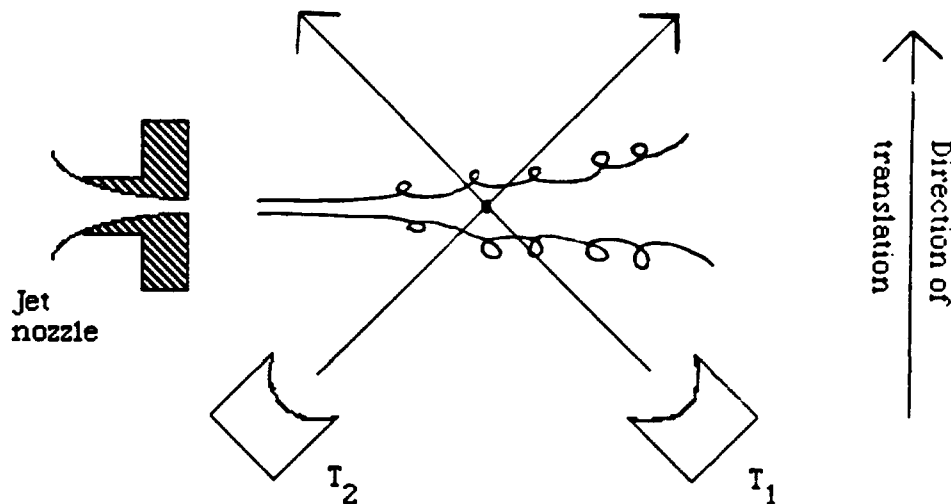


FIG 2. Geometry of translational scans

The second experiment involved the "conventional" scattering of one of the individual primary sound beams by the turbulence. Here, the scattered primary frequency's intensity spectrum is investigated. This experiment was identical in geometry to the first, except only one sound beam was translated across the turbulent jet. In both experiments, the relative angles for both of the transmitter beam axes and receiver beam axis were constant throughout the data run. From the collection of scattered sum frequency intensity spectra (from the crossed beam experiment) measured across the jet, Korman and Rife discovered that the rms radial component of turbulent velocity is directly proportional to the rms acoustic pressure of the scattered sum frequency. This relationship demonstrated the apparatus's ability to spatially resolve components of the turbulence along the line of forward scattering (or the line of bisection of the primary beam axes). In addition, Korman and Rife found that the skewness and

kurtosis of the scattered spectra matched the expected properties of skewness and kurtosis of the turbulent radial velocity correlations distributed across the jet. They verified that the spectral shape must be related to the probability density function for the turbulent velocities. In contrast, the scattered spectra for the "conventional" scattering of a single primary beam experiment showed much less correlation with the turbulent flow. It lacked good spatial resolution and could not predict either radial or axial turbulent flow profiles across the jet. The usefulness of nonlinear crossed beam scattering over "conventional" single beam scattering is now apparent. The successes of these earlier works have motivated this focused beam experiment.

In our experiment, the intensity spectra are measured as a function of angle at many scan positions across the width of the turbulent jet. This data will be used to determine the nonlinearly scattered sum frequency intensity spectrum versus angle as well as the statistical nature of the turbulent velocity components (since the turbulent velocity distribution in the jet is anisotropic). Measurements of the Doppler shift, variance, skewness, and kurtosis of the scattered spectra are used to predict the statistical turbulent velocity information involving the axial and radial direction of flow. The exact relations between the nonlinearly scattered spectral shapes and the turbulent velocities will be fully developed in the theory section of this paper.

EXPERIMENTAL SETUP

A. Scattering geometry

The geometry of the scattering problem involving two ultrasonic focused beams and turbulence is chosen to reflect a high degree of symmetry. The mutually perpendicular focused beams are generated from two individual transducer units of identical construction. Each transducer unit has a focal length of 14 cm. The beams are aligned to be mutually perpendicular and to overlap at a common focal point (Fig. 3).

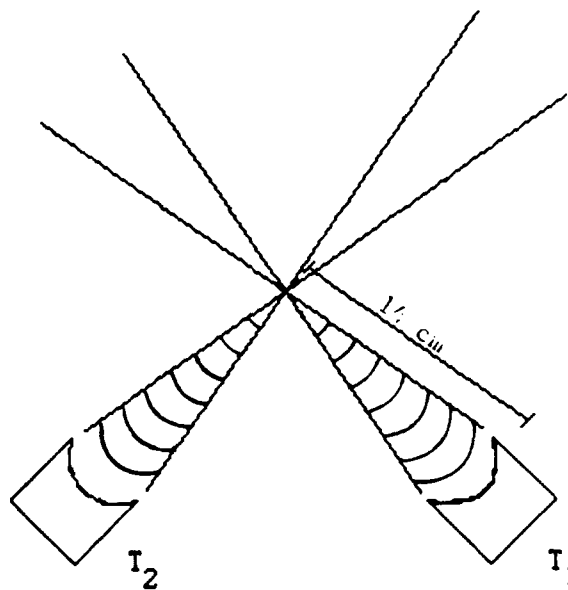


FIG. 3. Arrangement of focused transducers

Both transmitting transducers generate continuous wave focused beams of frequencies $f_{01} = 2.0$ MHz and $f_{02} = 2.1$ MHz, respectively. Focused beams are produced because the face of each transducer forms a spherical concave surface. The diameter of each surface is 2.54 cm. The transducers are designed to resonate at 2 MHz. However, the low Q factor

allows them to be driven off resonance and still generate large pressure amplitudes. Each transducer unit is submerged in the tank and individually attached to a radius arm that is mechanically suspended above the tank on a rotary table. A third receiving transducer unit is placed in the tank outside the interaction region. The receiver is an unfocused circular plane array transducer of diameter = 2.54 cm. This unit is designed and tuned for maximum detection response at a frequency of $f_{0+} = f_{01} + f_{02} = 4.1$ MHz. The low Q factor of the receiver unit allows the detection of a small range of frequencies around 4.1 MHz with a flat frequency response. The receiving transducer is not focused because it is extremely difficult to keep three focal points in alignment for long periods of time. Although the receiver is not focused, it is directional with a half power beam full width of 0.85 degrees. This directional axis is arranged to meet perpendicularly with the axis of the submerged circular jet and cross the jet at the interaction region (Fig. 4). The distance from the face of the receiving transducer to the interaction region is 15 cm.

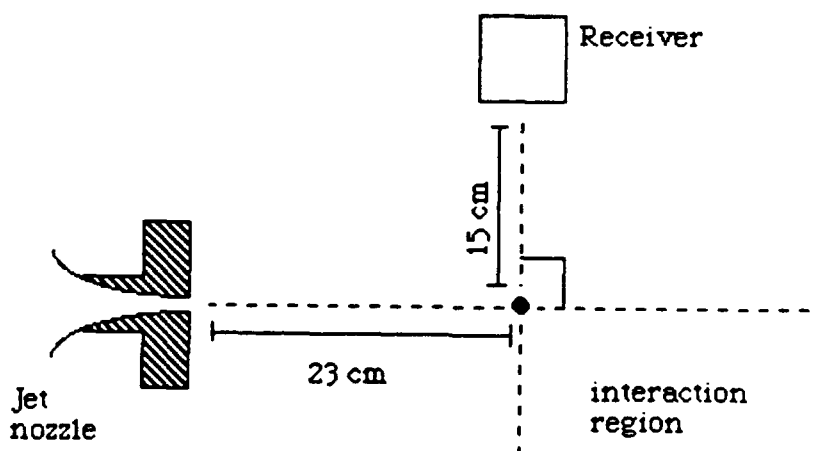


FIG 4. Arrangement of receiving transducer relative to the jet

This geometry is useful because the resulting scattering of the sum frequency components have their rays perpendicular to the jet's mean flow. Therefore, this component will not undergo further Doppler shifting as it propagates outside of the interaction region. Thus, one does not have to worry about the effects of rescattering of the sum frequency component.

Using this apparatus, two experiments are performed. The first is a fixed angle scan across the width of the jet, similar to Rife's work. Here, the two senders and receiver remain at fixed angle relative to each other while they are translated across the jet. These "translation scans", as depicted in Fig. 5, move the interaction region laterally to scan the turbulence perpendicular to the mean flow. The x-axis in Fig. 5 is along the radial direction.

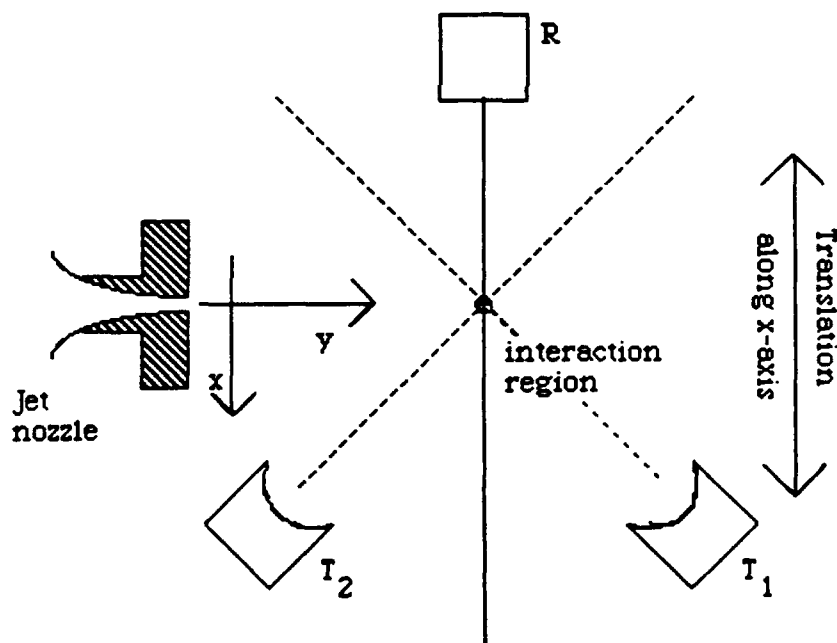


FIG 5. Geometry of transducers and jet during translational scans

In the rectangular coordinates given above, the overlap region maintains a constant position of $z = 0$ d and $y = 33.9$ d while x traverses from -8 d to $+8$ d, where d represents the diameter of the nozzle exit (0.25 inch = 0.635 cm). Two experiments are performed: "forward scattering" with the two senders facing towards the receiver ($\theta_1 = 45^\circ, \theta_2 = -45^\circ$) and "back scattering" with the two senders facing away from the receiver ($\theta_1 = 225^\circ, \theta_2 = 135^\circ$). Fig. 6 illustrates the relative transducer positions for "forward" and "back" scattering.

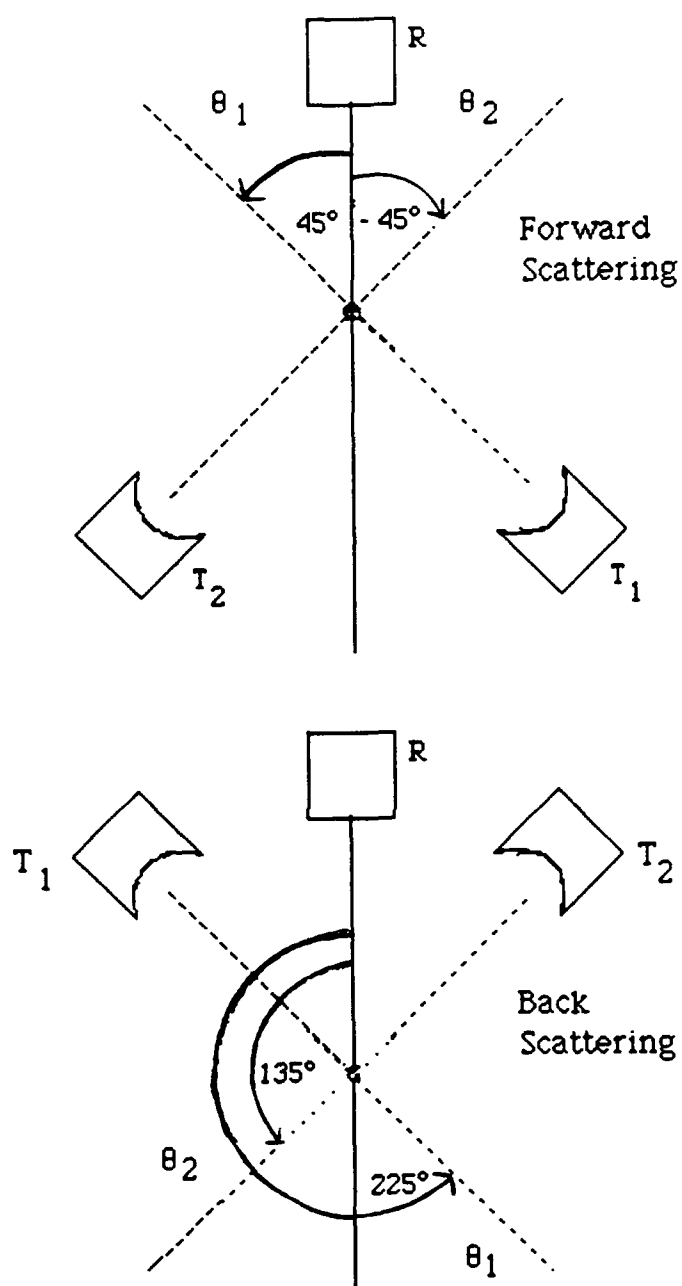


FIG. 6. Geometry of forward and back scattering experiments

The second experiment involves rotating the two transmitting transducers in a plane parallel to the water's surface. Throughout the experiment, the radius arms maintain the beam axes at right angles to each other while allowing

them to pivot about an axis perpendicular to the surface of the water and through the point of overlap. The receiver remains stationary at one scan position along the x-axis as the scattering angle is changed. A full 360° of scattering measurements is completed in 3° increments. After the apparatus has completed a 360° rotation, (which we shall call a complete data run) all three transducers are translated 0.2 inches along the x-axis using the mechanical translating carriage located above the tank. Then another data run is performed. We completed twelve successful runs covering 0.0 to 2.0 inches along the x-axis in steps of 0.2 inches. Note that gaps exist in the data at certain angular sectors. These gaps are caused because the transducers would be placed in the jet if a scan was performed at that angle. This would interfere with the jet and knock the transducers out of alignment so these sectors were skipped. Each data run took two or three days to complete. This is due partly because at each angle it took 45 seconds to electronically sweep and detect one spectrum. It was necessary to sweep 20 times to get one average spectrum.

B. Transmitting and Receiving Electronics

Measurements of the Doppler shift in the sum frequency spectrum require an absolute calibration of frequency of 10 Hz in 4.1 MHz. To insure that no drift occurs in our primary signals (that will raise questions upon the accuracy of the Doppler measurements), it is necessary to require excellent frequency stability. Two entirely separate but nearly identical crystal oscillator circuits are designed to generate the two primary electronic frequencies f_{01} ($= 2.006944$ MHz) and f_{02} ($= 2.100609$ MHz) with high stability. Fig. 7 presents an overview of the transmitting electronics in block format.

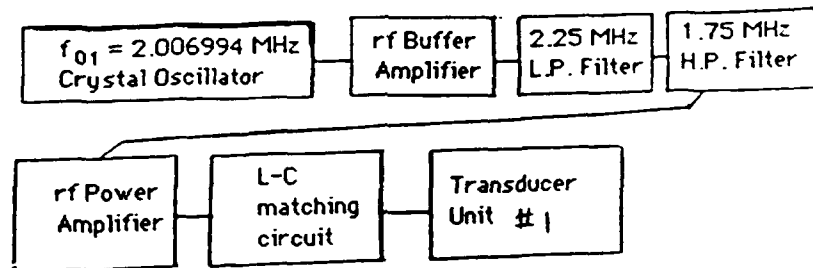


FIG 7. Transmitting electronics

A buffer amplifier protects the crystal oscillator from voltage fluctuations which could affect the amplitude and frequency of the oscillator's signal. Next, the signal is fed through 50 ohm five stage Butterworth low and high pass filters (2.25MHz and 1.75 MHz cut-off frequencies, respectively) to insure the signals are pure sinusoids with virtually no harmonic distortion. Finally, a 50 ohm, broad band, 100W radio frequency power amplifier increases the signal's amplitude. An L-C matching and tuning circuit is used to couple this power into each transmitting transducer unit. Thus, the sound generated is a pure tone at a frequency equal to f_{01} or f_{02} . The electronic signal amplitude is measured to be 60 volts peak to peak across the transducer input cable.

The receiving transducer and electronic instrumentation detect the relatively weak sum frequency pressure while filtering out the intense primary frequencies f_{01} and f_{02} that can also insonify the receiving transducer. A block diagram of the receiving electronics is presented in Fig. 8.

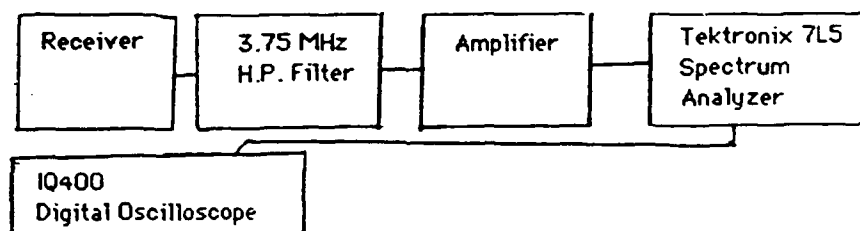


FIG. 8. Receiving Electronics

A 50 ohm BNC cable connects the 4.1 MHz receiver to a high pass filter. This 5 stage 50 ohm Chebyshev passive high pass filter has a 3 dB cutoff frequency at 3.75 MHz. The filter insures that no 2.0 or 2.1 MHz signals are present in the amplifier or spectrum analyzer electronics. If these low frequency signals are allowed to exist, the spectrum analyzer circuitry will electronically mix them nonlinearly, which will produce a sum frequency on its display. This electronically generated sum frequency is highly undesirable since it would deteriorate the ability to measure the acoustically generated sum frequency component.

Since this laboratory facility was not shielded from outside radio frequency transmissions, all electronic devices are placed in metal shielded boxes, and all connections between components are made with 50 ohm coaxial cables. This precaution insures that the signals received by the spectrum analyzer are generated acoustically at the receiving transducer. After the high pass filter, a low noise, linear, radio frequency amplifier amplifies the sound signal and outputs it to a Tektronix 7L5 Sweep Spectrum Analyzer. Here, the frequency components of the incoming signal are decomposed using a 30 Hz resolution sweep filter. The voltage amplitude at each frequency is digitized by an IQ400 Digital Oscilloscope which

then averages the results of twenty signal sweeps and stores the resulting spectra to disk on a Macintosh Plus computer for later analysis. The IQ400 digitized at 12 bits over a ± 200 mV range for 1024 points, with a sample time interval of 50 msec.[§]

C. Turbulence

A submerged circular water jet generates the turbulence in our experiment. This jet is formed from a 1/4 inch (0.635 cm) diameter nozzle and powered by a 1/8 hp centrifugal water pump. The pump creates 4.15 psi of pressure which was used to predict a nozzle exit velocity of $U_0 = 7.1$ m/s. Care is taken to insure that there is a high degree of laminar flow at the nozzle exit. Therefore, turbulent shear flow is generated by fluid flow mechanisms that are dominated by entrainment, turbulent mixing, vortex stretching, and nonlinear diffusion mechanisms. Care was taken so that turbulent flow does not develop from turbulence that already exists at the jet exit. Such "pre-jet" turbulence can be created from turbulent flows in the pump hoses and fittings leading to the nozzle. A "clean jet" or laminar jet at the nozzle exit is accomplished by introducing a plenum chamber prior to the exit. Fig. 9 shows the location of the plenum and other parts of the turbulence generation apparatus.

[§] In designing the experiment, care was taken to choose a sum frequency component that would not be close to the high powered radio frequencies generated at the North Severn Naval Station, Annapolis, MD. This fact had forced a design change from a planned 4.0 MHz sum frequency to 4.1 MHz.

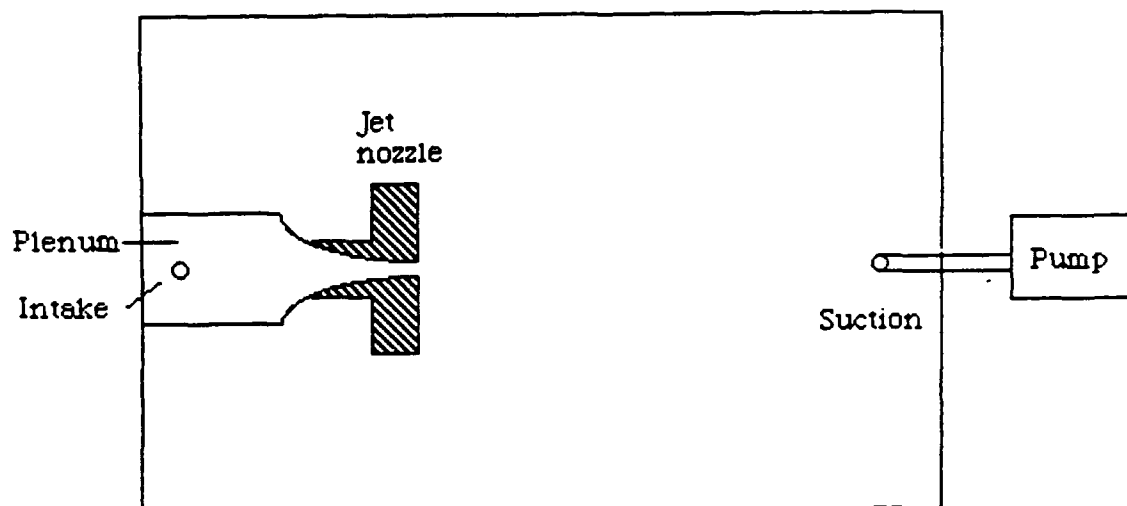


FIG. 9. Turbulence generation apparatus

The plenum mitigates any turbulent motion by allowing the flow cross-section to expand over an extended region. From the equation of continuity for incompressible fluid flow, the ratios of the cross-sectional areas at two points in a flow must be inversely proportional to the velocities at those same two points. The cross-sectional area of the plenum is 36 sq. inches. The one inch diameter hose leading into it has a cross-section of 0.78 sq. inches. Therefore, the velocity of the water must decrease by a factor of about 46. The turbulent motion in the plenum (a small fluctuation of the mean flow) will reduce by the same factor.

The plenum connects to a conical section (Fig. 10) that reduces the flow from a 6 inch diameter to a 3 inch diameter over a length of 6.25 inches.

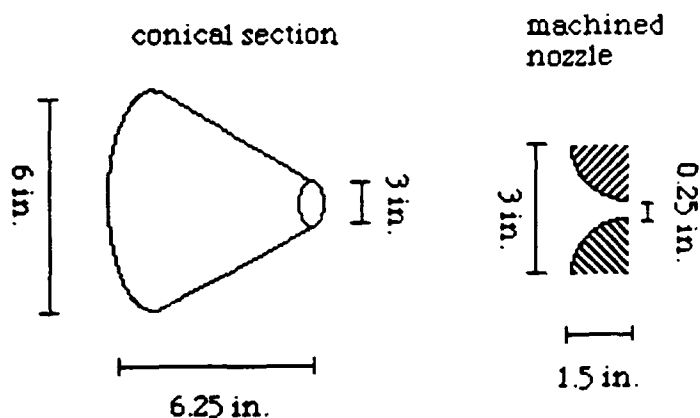


FIG. 10. Nozzle construction

This conical section connects to a high strength epoxy nozzle (Fig. 10) that gradually reduces the 3 inch diameter flow down to a 1/4 inch over a 1.5 inch distance. This nozzle is poured and set into a machined aluminum mold that is manufactured and shaped on a computer driven lathe cutter. The machining was performed in the Rickover Hall Machine Shop under the supervision of Mr. Carl Owen. The nozzle shape is designed to keep the flow highly laminar in the nozzle throat. The turbulence from this jet (laminar at the exit) can now be compared with other jets that are documented in the literature.

D. Mechanical and Computer Control

The experiment is performed with the assistance of computer control and mechanical automation because of the length of time required to complete a data run. Translational runs (at a fixed angle) take twenty four hours each, while rotational scans (at a fixed scan position) require several days. An Apple IIe is chosen for the computer control because of its ease in programming and for its ability to interface with

several very different machines. The Apple IIe controls a stepper motor to position the transducers at the appropriate scattering angle for each data sweep, while for the translational runs. Another stepper motor is controlled by the Apple IIe to move a piston that in turn pushes a carriage with grooved wheels mounted on two inverted "V" tracks that are supported above the tank. The orientation of the carriage and tracks with respect to the jet is shown in Fig. 11.

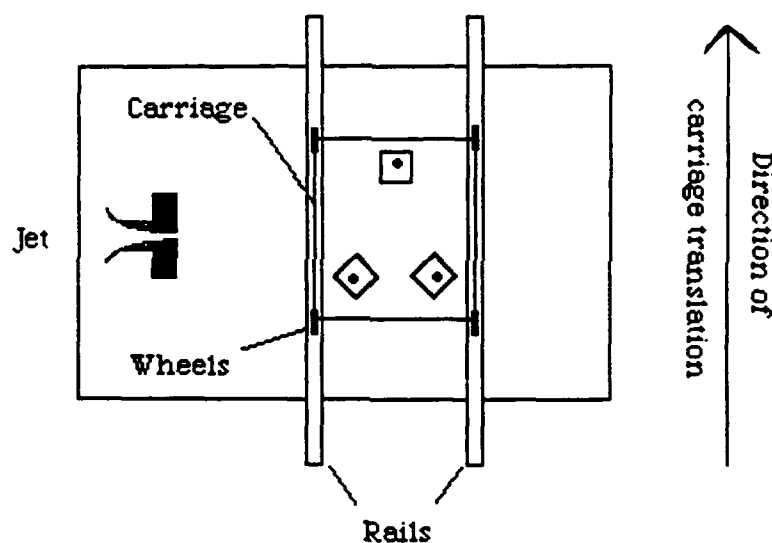


FIG. 11. Translational carriage orientation

Since the tracks are parallel to the x-axis, the carriage moves all three transducers along the width of the jet. In the rotational mode, a stepper motor and a reduction gear box turn the crankshaft on a rotary table. The radius arms of the sending transducers are mounted on this table. The two senders rotate in a plane parallel to the water's surface.

Communication with the spectrum analyzer involves triggering the spectrum analyzer's single sweep control. This is

accomplished by dedicating a digital switch to trigger the 7L5 at the appropriate time determined by an Apple program. A ramp signal from the 7L5 sweep time base then triggers the IQ400 to trigger its acquisition mode. The Apple IIe also controls the IQ400 by an IEEE-488 GPIB interface bus. This link allows the Apple to control the IQ400 to signal average the incoming spectra, direct the IQ400 to save each spectrum to a Macintosh Plus computer for future analysis, and keep track of scan position, rotation angle and the labeling of the data. The computer programs and associated documentation are presented in appendix C.

THEORETICAL DISCUSSION

A. Overview

The theory involving the nonlinear interaction of crossed ultrasonic beams is greatly simplified if the interaction involves incoming plane waves. In order to use Korman and Beyer's theory⁵, we must model the focused incoming beams as plane waves inside the tightly defined interaction region where the two beams overlap. The focused transducers do not actually emit plane waves; however, since the curvature of the wave fronts is small compared to the size of the overlap region, the plane-wave approximation is acceptable. Thus, we are justified in using Korman and Beyer's plane wave theory⁵ for our experiment.

Of particular importance to the experiment is the Doppler shift equation, $\omega_d = \vec{K}_+ \cdot \vec{V}$, which relates the magnitude of the Doppler shift to the sum frequency component's wavenumber and the velocity of the turbulence. We will now discuss the Doppler phenomenon in general so that the reader can become familiar with its use in the crossed beam experiment.

A Doppler shift is a change of frequency due to the relative motion between a sound source and a receiver. A common example is the rising pitch of a train whistle as it approaches a stationary observer at a train station. In the case where the train is approaching, the train's whistle closes in on the sound waves in front of it. The wavelengths of sound then become shorter. This increases the sound's frequency which you hear as a higher pitch. In our case, the sources are tiny packets of sound wavelets formed in the overlap region by the interaction of the crossed sound beams and the turbulent scattering sites. These packets of sound sources (or phonons) are jostled around by the action of the turbulence which creates a relative motion between the wavelets and the stationary 4.1 MHz receiver. Thus, although the "phonons" are

theoretically emitting a pure 4.1 MHz tone, their relative motion toward or away from the receiver causes the receiver to detect a Doppler shifted frequency that can be higher or lower than the 4.1 MHz tone. The Doppler shifted frequency is given by $f_{0+} + f_d$ where $f_d = \frac{\omega_d}{2\pi} = \frac{\vec{K}_+ \cdot \vec{V}}{2\pi}$.

This equation for Doppler shifts is used to relate the shape of a scattered sum frequency spectra to the time averaged turbulent velocity quantities.

Unlike the train whistle which has only one shift in frequency, the scattered sum frequency has several shifts. Correctly speaking, it has a band of shifts. Each scattered wavelet is caused by a turbulent eddy in the overlap region that has a characteristic velocity. Since the turbulent eddies or scattering sites that generate different waves varies spatially over the interaction region and with a velocity that can change with time, each wavelet is jostled by a different amount depending upon the local motion of the turbulent jet. This causes several different tones to be detected at the receiver. All tones are around f_{0+} but some are above it (the turbulent eddy moves toward the receiver) and others are below (the turbulent eddy moves away from the receiver). The net result is to smear the pure tone f_{0+} over a band of frequencies centered around f_{0+} . Therefore, the net result is that the scattered sum frequency component is detected as a scattered spectrum of frequencies. This spectrum is called the nonlinearly scattered intensity spectrum.

The shape of the scattered spectra is quantified by calculating the average frequency $\langle f \rangle$, variance σ^2 , skewness S , and kurtosis K of the scattered spectra. In our research group these are called the shape factors. These spectral quantities, ($\langle f \rangle$, σ^2 , S , and K) each describe a specific contribution to the broadened scattered sum frequency spectrum which can be related to the vector turbulent velocities that are the cause of the Doppler shifts. The average (or most probable) frequency in the scattered spectrum is due

to the mean or average velocity of the turbulent eddies in the overlap region. This frequency is given by $\langle f \rangle = \langle f_{0+} + \omega_d / 2\pi \rangle = f_{0+} + \langle \vec{K}_+ \cdot \vec{V} \rangle / 2\pi$, where \vec{V} is the instantaneous velocity of the scattering eddies. If $\vec{V} = \vec{V}_0 + \vec{V}'$, where \vec{V}_0 is the average velocity and \vec{V}' is the fluctuating portion, then the time average Doppler shift $\langle f \rangle$ can be expressed by $\langle f \rangle - f_{0+}$ which is $\langle f_d \rangle \equiv \langle f \rangle - f_{0+} = (\vec{K}_+ \cdot \langle \vec{V} \rangle) / 2\pi$.

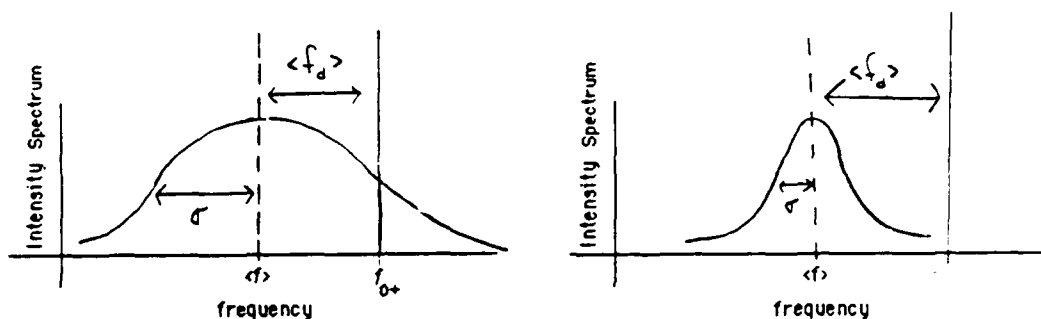


FIG. 12. Illustration of Doppler shift and variance

In Fig. 12, the broadened curve represents the measured scattered intensity spectrum versus frequency. The spike at f_{0+} is the pure tone of the sum frequency which has been smeared out to give the observed spectrum. Define $\langle f \rangle$ to be the average frequency of the spectrum. It is determined from the mathematical expression

$$\langle f \rangle = \frac{\int I(f) f df}{\int I(f) df}.$$

One can compute the variance of the spectrum. The standard deviation, σ , is the rms frequency and is a measure of the width of the spectrum. Mathematically, σ^2 is given by

$$\sigma^2 = \frac{\int I(f) (f - \langle f \rangle)^2 df}{\int I(f) df}.$$

The magnitude of the turbulent velocity fluctuations in an interaction region determines the broadening of the sum frequency spectra. If the velocity fluctuations in the interaction region are large, then the distribution of Doppler shifts "heard" and the spectral broadening will be large as in the diagram at the left in Fig. 12. Conversely, if there are only small velocity fluctuations, then there will be only a small distribution of Doppler shifts and the spectra will be narrow which is shown by the diagram at the right in Fig. 12.

Skewness indicates a bias in the spectra towards one side of the frequency spectrum or the other. Intensity spectra exhibiting positive and negative skewness are shown in Fig. 13.

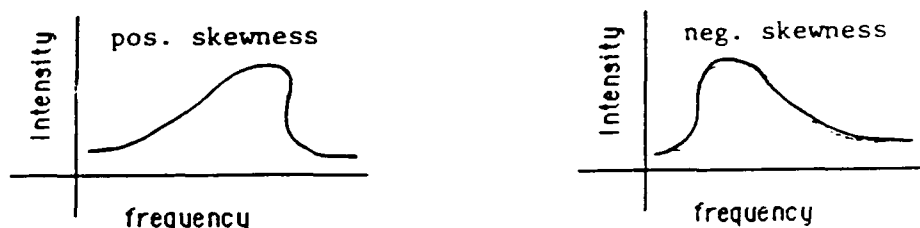


FIG. 13. Comparison of positive and negative skewness

Skewness, S , is determined mathematically from the third moment of the spectrum. It is given by

$$S = \frac{\int I(f) (f - \langle f \rangle)^3 df}{\sigma^3}.$$

For a gaussian or any symmetric distribution function, the skewness is always equal to zero, indicating no bias. If the turbulent velocity fluctuations spend more time moving toward the receiver than away from it, then the intensity spectrum will exhibit a positive skewness, S . In contrast, a negative skewness means that the velocity fluctuations spend more time moving away from the receiver than toward it.

The last spectral shape property is called the Kurtosis which describes the intermittency or bursting phenomenon of a probability distribution.

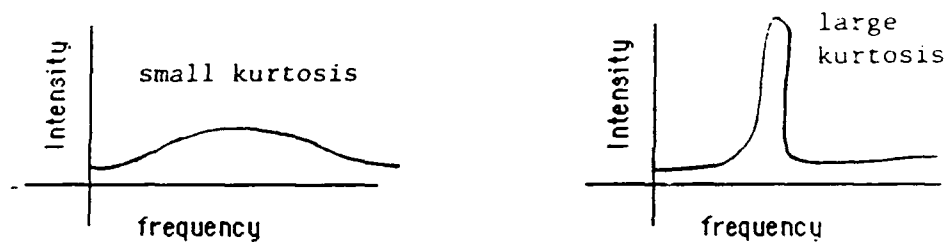


FIG. 14. Comparison of distributions exhibiting large and small kurtosis

Define the kurtosis, K , to be given by

$$K = \frac{\int I(f) (f - \langle f \rangle)^4 df}{\sigma^4}.$$

In Fig. 14, the graph at left exhibits a small kurtosis. This distribution represents a turbulent fluctuation that is steady and does not change much in time. In contrast, the graph on the right in Fig. 14 is related to a distribution with a very large kurtosis. This would describe a particle that has at first a

period of steady fluctuations, then suddenly exhibits large bursts of velocity changes which later go back to being steady fluctuations. For a Gaussian distribution, the kurtosis is equal to three, which is often used as a comparison to other distributions.

With these descriptions of the spectral distributions, we can discuss the nonlinear crossed beam spectral theory. From our initial hypothesis that the focused beams will create locally plane waves within the overlap region, one can make use of Korman and Beyer's theory⁵ with plane waves. From their nonlinear scattering theory, they derived an equation to define the Doppler shifts of the scattered sum frequency component, $\omega_d = \vec{K}_+ \cdot \vec{V}$. Using this equation, one can extract values for the turbulent velocity fluctuations (as statistical quantities) from the experimentally determined scattered sum frequency spectrum measured as a function scattering angle. To describe this method, one first defines these symbols:

- ω_d = Doppler shift of the sum frequency in rad/sec
- \vec{K}_+ = wavenumber vector of the scattered sum frequency component
 $= \vec{K}_1 + \vec{K}_2$
- \vec{K}_1 = scattered wavenumber vector corresponding to scattering from a conventionally scattered single sound beam originating from Transducer #1
 $= k_{01}(\vec{n} - \vec{n}_{01})$
- \vec{K}_2 = similar definition for the sound beam emitted by Transducer #2
- k_{01}, k_{02} = magnitude of the wavenumber from transducer #1, transducer #2
 $= \omega_{01}/c, \omega_{02}/c$
- ω_{01}, ω_{02} = angular frequency (rad/sec) emitted from transducer #1, transducer #2
- c = speed of sound in water (1482 m/s at 20°C)
- \vec{n} = unit vector pointing towards the receiver

\mathbf{n}_{01} = unit vector pointing along original path of beam#1
 \mathbf{n}_{02} = unit vector pointing along original path of beam#2.

Fig. 15 illustrates the relationships between \mathbf{n} , \mathbf{n}_{01} , and \mathbf{n}_{02} .

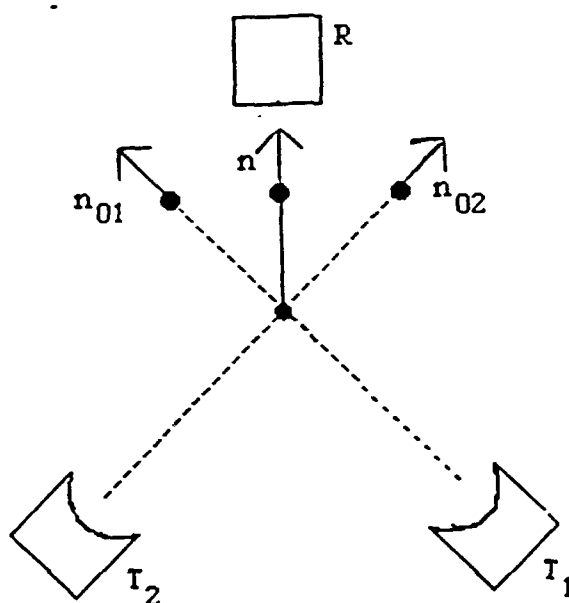


FIG.15. Incident and scattered sound beam geometry

Both transmitting transducers are free to rotate in the plane described in Fig. 16. The angles, θ_1 and θ_2 , are used to define their angular positions with respect to the receiver axis and each of the respective transmitting axes. Since the relative angle between the two transmitting transducers is always maintained at 90° , a single scattering angle, θ_* , can be used to describe the transducer positions. Express the scattering angles θ_1 and θ_2 in terms of the symmetry angle θ_* by

$$\theta_1 = \theta_* + 45^\circ,$$

$$\theta_2 = \theta_* - 45^\circ.$$

This symmetry is shown in Fig. 16.

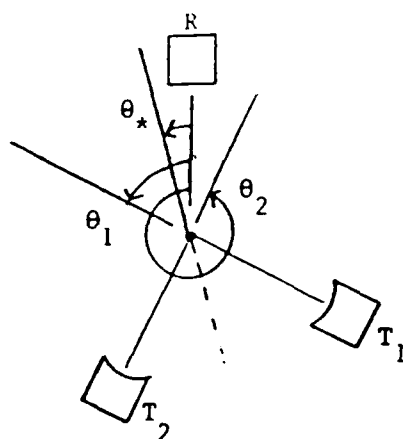


FIG. 16. Illustration of the angular relationships

It is important to recognize that two rectangular coordinate systems must be developed to completely define the scattering geometry (Fig. 17). The first matches the usual polar coordinate system set up by the orientation of the transducers. The second defines the normal coordinate system from the jet's point of view.

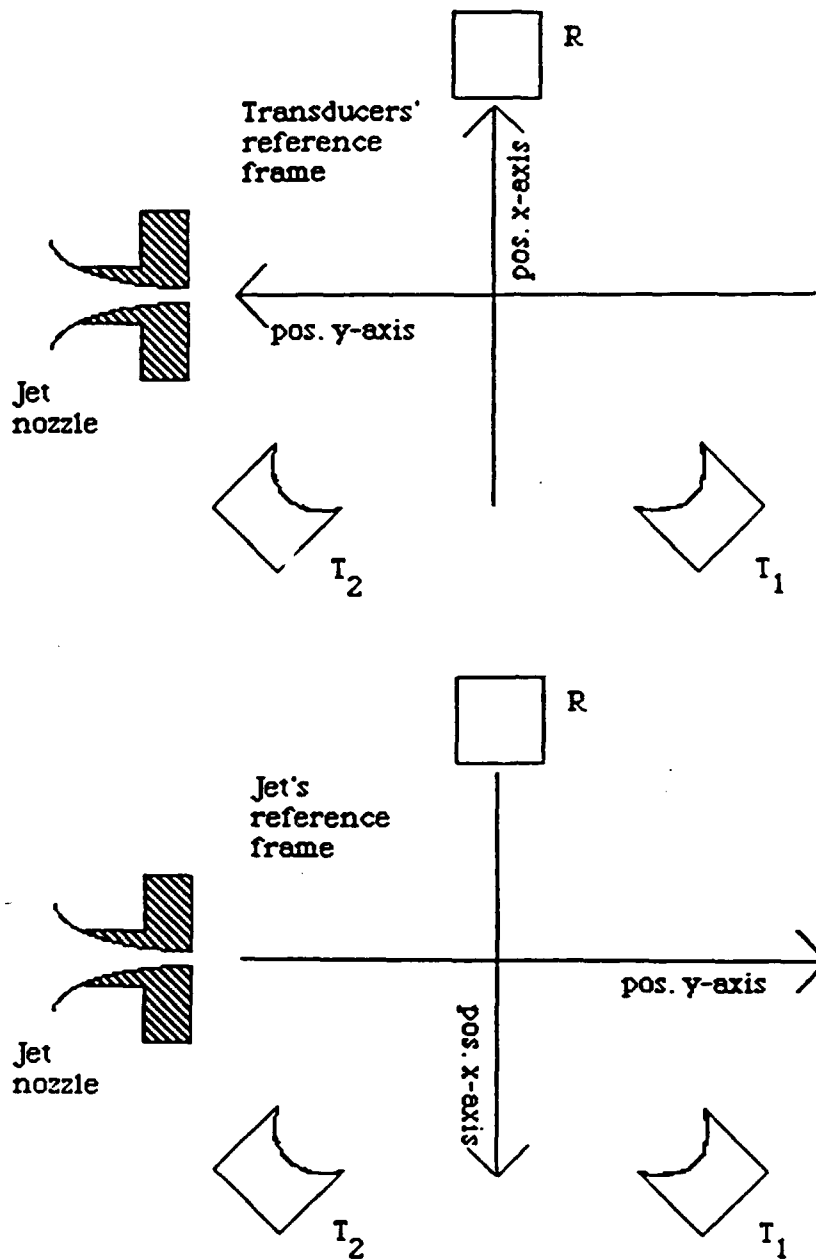


FIG.17. Comparison of normal coordinate systems

Notice the inversion of the x-y plane between the two systems. Measurements in the x-y plane of one system will have the opposite sign in the other. This forces a negative sign to the equation for Doppler shifts to maintain consistency between the systems, so $\omega_d = -(\vec{K}_+ \cdot \vec{V})$.

To model the turbulent flow, let $\vec{V} = (V_{0x} + V_x)\mathbf{i} + (V_{0y} + V_y)\mathbf{j}$

where

V_{0x} = mean velocity in the x direction

V_{0y} = mean velocity in the y direction

V_x = turbulent velocity fluctuations in the x direction

V_y = turbulent velocity fluctuations in the y direction.

The turbulent velocity fluctuations average to zero. This is expressed by $\langle V_x \rangle = 0$, and $\langle V_y \rangle = 0$, where the brackets around a variable denote an average of that variable over time.

Now the definitions of $\langle f \rangle$, σ^2 , S , and K can be related to four different spectral moments which are constructed from ω_d . It will be shown later that these four moments will yield linear combinations of turbulent velocity moments. These moments are often referred to as correlation coefficients of the turbulence.

The theory is now outlined below:

$$\begin{aligned}\omega_d &= -(\vec{K}_+ \cdot \vec{V}) && \text{from Korman and Beyer}^5 (1) \\ &= -(\vec{K}_1 + \vec{K}_2) \cdot \vec{V}\end{aligned}$$

$$\vec{K}_1 \approx k_{01}(\mathbf{n} - \mathbf{n}_{01}) \quad \text{definition}$$

$$\vec{K}_2 \approx k_{02}(\mathbf{n} - \mathbf{n}_{02}) \quad \text{definition}$$

$$\vec{V} = (V_{0x} + V_x)\mathbf{i} + (V_{0y} + V_y)\mathbf{j} \quad \text{turbulent eddy's velocity vector}$$

$$\mathbf{n}_{01} = \mathbf{i} \cos(\theta_1) + \mathbf{j} \sin(\theta_1) \quad \text{unit vectors in the direction}$$

$$\mathbf{n}_{02} = \mathbf{i} \cos(\theta_2) + \mathbf{j} \sin(\theta_2) \quad \text{of each incident, primary wave}$$

$$\vec{K}_1 = k_{01}[(1 - \cos(\theta_1))\mathbf{i} - \sin(\theta_1)\mathbf{j}] \quad (2)$$

$$\vec{K}_2 = k_{02}[(1 - \cos(\theta_2))\mathbf{i} - \sin(\theta_2)\mathbf{j}] \quad (3)$$

$$\begin{aligned}\vec{K}_1 + \vec{K}_2 &= [k_{01}(1 - \cos(\theta_1)) + k_{02}(1 - \cos(\theta_2))]\mathbf{i} \\ &\quad - [k_{01}\sin(\theta_1) + k_{02}\sin(\theta_2)]\mathbf{j} .\end{aligned} \quad (4)$$

We can write this expression in terms of θ , by using this transformation:

$$\begin{aligned}
 \theta_1 &= \theta_* + 45^\circ \\
 \theta_2 &= \theta_* - 45^\circ \\
 \vec{K}_+ &= k_{0+} \left(1 - \frac{\sqrt{2}}{2} \cos \theta_* - \gamma \sin \theta_* \right) \mathbf{i} + k_{0+} \left(-\frac{\sqrt{2}}{2} \sin \theta_* - \gamma \frac{\sqrt{2}}{2} \cos \theta_* \right) \mathbf{j} \quad (5a)
 \end{aligned}$$

where

$$\begin{aligned}
 k_{0+} &= k_{01} + k_{02} \\
 k_{0-} &= k_{01} - k_{02} \\
 \gamma &= k_{0-} / k_{0+}
 \end{aligned}$$

Let

$$K_x = k_{0+} \left(1 - \frac{\sqrt{2}}{2} \cos \theta_* - \gamma \sin \theta_* \right) \quad (5b)$$

$$K_y = k_{0+} \left(-\frac{\sqrt{2}}{2} \sin \theta_* - \gamma \frac{\sqrt{2}}{2} \cos \theta_* \right), \text{ then} \quad (5c)$$

$$\omega_d = -[K_x \mathbf{i} + K_y \mathbf{j}] \cdot [(V_{ox} + V_x) \mathbf{i} + (V_{oy} + V_y) \mathbf{j}].$$

By substitution,

$$\omega_d = -[K_x(V_{ox} + V_x) + K_y(V_{oy} + V_y)]. \quad (6)$$

Since the instantaneous values of the Doppler shift depend upon the instantaneous velocities of the turbulence, which are constantly fluctuating, we are more interested in time averaged values,

$$\langle \omega_d \rangle = -[K_x(V_{ox} + \langle V_x \rangle) + K_y(V_{oy} + \langle V_y \rangle)].$$

Since K_x , V_{ox} , K_y , and V_{oy} are all constant with respect to time,

$$\langle \omega_d \rangle = -(K_x V_{ox} + K_y V_{oy}). \quad (7)$$

Now we relate the average Doppler shift to the average frequency,

$$\langle f \rangle = f_{0+} - \langle f_d \rangle \quad (8)$$

$$\langle f \rangle = f_{0+} - \langle \omega_d \rangle / 2\pi ;$$

which yields a relation from which we can extract the mean velocity of the jet using our scattered spectra

$$\langle f \rangle - f_{0+} = (K_x V_{ox} + K_y V_{oy}) / 2\pi . \quad (9)$$

To set up the second, third, and fourth moments, define the quantity $\omega_d - \langle \omega_d \rangle$ below:

$$\omega_d - \langle \omega_d \rangle = -(K_x V_x + K_y V_y) . \quad (10)$$

The second moment denoted by $\sigma^2 = \langle (\omega_d - \langle \omega_d \rangle)^2 \rangle$, becomes

$$\begin{aligned} \langle (\omega_d - \langle \omega_d \rangle)^2 \rangle &= \langle (K_x V_x + K_y V_y)^2 \rangle \\ &= K_x^2 \langle V_x^2 \rangle + 2K_x K_y \langle V_x V_y \rangle + K_y^2 \langle V_y^2 \rangle . \end{aligned} \quad (11)$$

Similarly, the third moment $= \langle (\omega_d - \langle \omega_d \rangle)^3 \rangle$ becomes

$$\begin{aligned} \langle (\omega_d - \langle \omega_d \rangle)^3 \rangle &= \langle (K_x V_x + K_y V_y)^3 \rangle \\ &= -K_x^3 \langle V_x^3 \rangle - 3K_x^2 K_y \langle V_x^2 V_y \rangle - 3K_x K_y^2 \langle V_x V_y^2 \rangle \\ &\quad - K_y^3 \langle V_y^3 \rangle . \end{aligned} \quad (12)$$

Using this relation, the skewness is defined to be

$$S = \langle (\omega_d - \langle \omega_d \rangle)^3 \rangle / \sigma^3 .$$

Finally, the fourth moment $= \langle (\omega_d - \langle \omega_d \rangle)^4 \rangle$ becomes

$$\begin{aligned} \langle (\omega_d - \langle \omega_d \rangle)^4 \rangle &= \langle (K_x V_x + K_y V_y)^4 \rangle \\ &= K_x^4 \langle V_x^4 \rangle + 4K_x^3 K_y \langle V_x^3 V_y \rangle + 6K_x^2 K_y^2 \langle V_x^2 V_y^2 \rangle + \\ &\quad 4K_x K_y^3 \langle V_x V_y^3 \rangle + K_y^4 \langle V_y^4 \rangle . \end{aligned} \quad (13)$$

Kurtosis is defined as:

$$K = \langle (\omega_d - \langle \omega_d \rangle)^4 \rangle / \sigma^4 .$$

From these relations of the average Doppler shifts (which come from statistical properties of the broadened sum frequency spectra), one can find $V_{ox}, V_{oy}, \langle V_x^2 \rangle, \langle V_x V_y \rangle, \langle V_y^2 \rangle, \langle V_x^3 \rangle, \langle V_x^2 V_y \rangle, \langle V_x V_y^2 \rangle, \langle V_y^3 \rangle, \langle V_x^4 \rangle, \langle V_x^3 V_y \rangle, \langle V_x^2 V_y^2 \rangle, \langle V_x V_y^3 \rangle$, and $\langle V_y^4 \rangle$ of the turbulent flow.

B. Isotropic turbulence

If one assumes that the turbulence is isotropic with respect to the randomly fluctuating velocity component, then the magnitudes of the fluctuations in the radial (x) and axial (y) directions are equal. This isotropic model allows the equations for σ^2 , S, and K to be simplified. Although this is an oversimplification, the resulting relationships between spectral moments and turbulent velocities are easy to visualize.

Let V equal the magnitude of the velocity fluctuations with components V_x and V_y given by

$$V_x = V \cos \alpha$$

$$V_y = V \sin \alpha,$$

where V and α are functions of time.

Here, one imposes the condition of isotropy by stating that V and α are statistically independent random variables. Using this model, the variance, σ^2 , becomes

$$\sigma^2 = K_x^2 \langle V^2 \cos^2 \alpha \rangle + 2K_x K_y \langle V^2 \cos \alpha \sin \alpha \rangle + K_y^2 \langle V^2 \sin^2 \alpha \rangle.$$

Since $\langle \cos^2 \alpha \rangle = 1/2$, $\langle \cos \alpha \sin \alpha \rangle = 0$, and $\langle \sin^2 \alpha \rangle = 1/2$,

$$\begin{aligned} \sigma^2 &= \langle V^2 \rangle [K_x^2 (1/2) + 0 + K_y^2 (1/2)] \\ &= (1/2) \langle V^2 \rangle [K_x^2 + K_y^2] . \end{aligned} \tag{14}$$

Since $K_x^2 + K_y^2$ is constant at a fixed scattering angle, σ^2 is proportional to the square of the turbulent velocity.

The expression for skewness becomes

$$S = (-K_x^3 \langle V^3 \rangle \langle \cos \alpha^3 \rangle - 3K_x^2 K_y \langle V^3 \rangle \langle \cos \alpha^2 \sin \alpha \rangle - 3K_x K_y^2 \langle V^3 \rangle \langle \cos \alpha \sin \alpha^2 \rangle - K_y^3 \langle V^3 \rangle \langle \sin \alpha^3 \rangle) / \sigma^3.$$

Since $\langle \cos \alpha^3 \rangle$, $\langle \cos \alpha^2 \sin \alpha \rangle$, $\langle \cos \alpha \sin \alpha^2 \rangle$, $\langle \sin \alpha^3 \rangle$ all = 0 ,

$$S = 0. \quad (15)$$

The expression for kurtosis becomes

$$K = K_x^4 \langle V^4 \rangle \langle \cos \alpha^4 \rangle + 4K_x^3 K_y \langle V^4 \rangle \langle \cos \alpha^3 \sin \alpha \rangle + 6K_x^2 K_y^2 \langle V^4 \rangle \langle \cos \alpha^2 \sin \alpha^2 \rangle + 4K_x K_y^3 \langle V^4 \rangle \langle \cos \alpha \sin \alpha^3 \rangle + K_y^4 \langle V^4 \rangle \langle \sin \alpha^4 \rangle / \sigma^4.$$

Since $\langle \cos \alpha^4 \rangle = 3/8$, $\langle \cos \alpha^3 \sin \alpha \rangle = 0$, $\langle \cos \alpha^2 \sin \alpha^2 \rangle = 1/8$, $\langle \cos \alpha \sin \alpha^3 \rangle = 0$, $\langle \sin \alpha^4 \rangle = 3/8$,

$$\begin{aligned} K &= \langle V^4 \rangle [K_x^4 (3/8) + 0 + 6K_x^2 K_y^2 (1/8) + 0 + K_y^4 (3/8)] / \sigma^4 \\ &= \langle V^4 \rangle \frac{(3/2)[(1/4)(K_x^4 + 2K_x^2 K_y^2 + K_y^4)]}{\langle V^2 \rangle^2 [(1/4)(K_x^4 + 2K_x^2 K_y^2 + K_y^4)]} \\ &= (3/2) K_{\text{turb}}. \end{aligned} \quad (16)$$

Here, K_{turb} is the kurtosis of the isotropic turbulent velocity fluctuations at the current scan point.

C. Anisotropic turbulence

The actual turbulent flow is anisotropic. Therefore, to find the turbulent velocities, one must use curve fitting techniques and apply the theoretical model of nonlinear scattering. Two methods are used to collect nonlinear scattered data. Therefore, there are two separate procedures used to develop curve fits. Once the theoretical model is fitted to the

actual shape factors of the scattered sum frequency spectra, then the turbulent velocity correlations can be predicted. Each method is described in the sections that follow.

APPLICATION OF THE SPECTRAL THEORY TO THE TRANSLATIONAL CASE OF CROSSED BEAM SCATTERING (θ_* FIXED)

The first experiment applies the spectral theory to the case of translating the crossed beams across the jet at a fixed angle. Two types of translational runs are attempted, "forward scattering" in which $\theta_* = 0^\circ$ and "back scattering" where $\theta_* = 180^\circ$. By solving the following system of equations from the Doppler shift relation, a closed form solution is derived to find the mean axial and radial velocities.

Modifying Eq. 7 from the spectral theory yields

$$\langle \omega_d \rangle = -[K_x(\theta_*)V_{ox} + K_y(\theta_*)V_{oy}] ,$$

which makes explicit the dependence of K_x and K_y on θ_* .

Substitute $\theta_* = 0^\circ$ and $\theta_* = 180^\circ$ into Eq. 7 along with the experimentally determined average Doppler shifts to create a system of two equations:

$$\langle \omega_d(\theta_* = 0^\circ) \rangle = -(K_x(0^\circ)V_{ox} + K_y(0^\circ)V_{oy}) \quad (17)$$

$$\langle \omega_d(\theta_* = 180^\circ) \rangle = -(K_x(180^\circ)V_{ox} + K_y(180^\circ)V_{oy}). \quad (18)$$

To determine V_{ox} and V_{oy} , first find K_x and K_y from Eqs(5b, 5c);

$$K_x(0^\circ) = k_{0+} - \frac{\sqrt{2}}{2} k_{0+}$$

$$K_y(0^\circ) = -\frac{\sqrt{2}}{2} k_{0-}$$

$$K_x(180^\circ) = k_{0+} + \frac{\sqrt{2}}{2} k_{0+}$$

$$K_y(180^\circ) = \frac{\sqrt{2}}{2} k_{0-} .$$

Substitution of these values and dividing through by ω_{0+} (to make all terms dimensionless) yields

$$\begin{aligned} \langle \omega_d(\theta_* = 0^\circ) \rangle / \omega_{0+} &= (V_{ox}[1 - \frac{\sqrt{2}}{2}] - V_{oy}[\frac{\sqrt{2}}{2}]\gamma) / c \quad \text{and} \\ \langle \omega_d(\theta_* = 180^\circ) \rangle / \omega_{0+} &= (V_{ox}[1 + \frac{\sqrt{2}}{2}] + V_{oy}[\frac{\sqrt{2}}{2}]\gamma) / c . \end{aligned}$$

$$\begin{aligned} \text{Let } g_f &= \langle \omega_d \rangle(\theta_* = 0^\circ) / \omega_{0+} \\ g_b &= \langle \omega_d \rangle(\theta_* = 180^\circ) / \omega_{0+} . \end{aligned}$$

The system can now be solved for the mean velocities which are given as

$$V_{ox} = (g_f + g_b)c / 2 \quad (19)$$

$$V_{oy} = \frac{2}{\sqrt{2}\gamma} [g_f \left(\frac{-1-\sqrt{2}/2}{2} \right) + g_b \left(\frac{1-\sqrt{2}/2}{2} \right)]c . \quad (20)$$

It is pointed out that the experimental measurements of the mean axial velocity, V_{oy} , may be subject to large errors if the beams are not aligned perfectly. If we let θ_{ER} be the size of the angular misalignment then, we can find a relation that will show how large our errors are due to the misalignment.

For $\theta_* = 0^\circ$

$$\sin(\theta_* + \theta_{ER}) \approx \theta_{ER}$$

$$\cos(\theta_* + \theta_{ER}) \approx 1 .$$

For $\theta_* = 180^\circ$

$$\sin(\theta_* + \theta_{ER}) \approx -\theta_{ER}$$

$$\cos(\theta_* + \theta_{ER}) \approx 1 .$$

By substituting these expressions into the definitions of $K_x(\theta_*)$ and $K_y(\theta_*)$

$$\begin{aligned} K_x(0^\circ) &= k_{0+}(1 - \frac{\sqrt{2}}{2} - \gamma \theta_{ER}) \\ &= k_{0+}(1 - \frac{\sqrt{2}}{2}) \\ K_y(0^\circ) &= k_{0+}(-\frac{\sqrt{2}}{2}\theta_{ER} - \gamma \frac{\sqrt{2}}{2}) \end{aligned}$$

$$\begin{aligned}
K_x(180^\circ) &\approx k_{0+}(1 + \frac{\sqrt{2}}{2} - \gamma \theta_{ER}) \\
&\approx k_{0+}(1 + \frac{\sqrt{2}}{2}) \\
K_y(180^\circ) &\approx k_{0+}(\frac{\sqrt{2}}{2}\theta_{ER} + \gamma \frac{\sqrt{2}}{2}).
\end{aligned}$$

Using these relations for $K_x(\theta_*)$ and $K_y(\theta_*)$ and solving Eqs. 17 and 18 similarly to before, we get the following relations:

$$V_{ox} = (g_f + g_b)c / 2 \quad (19')$$

$$V_{oy} = (1/\Gamma) \frac{2}{\sqrt{2}} [g_f \left(\frac{-1-\sqrt{2}/2}{2} \right) + g_b \left(\frac{1-\sqrt{2}/2}{2} \right)] c, \quad (20')$$

$$\text{where } \Gamma = \theta_{ER} + \gamma.$$

Note that small errors in alignment introduce no error in the measurements of the mean radial velocity. However, alignment errors are a considerable factor in the measurements of the mean axial velocity. Since the ratio of $k_{0-}/k_{0+} = \gamma = 0.0228$ for our crossed beam experiment, an angular error of 0.0228 radians (1.3 degrees) in the alignment of the transducers will introduce a factor of two error in the measured value of mean axial velocity.

Further analysis of the scattering geometry leads to the discovery that the effective beamwidth of the transmitting transducers will also contribute to the error factor Γ .

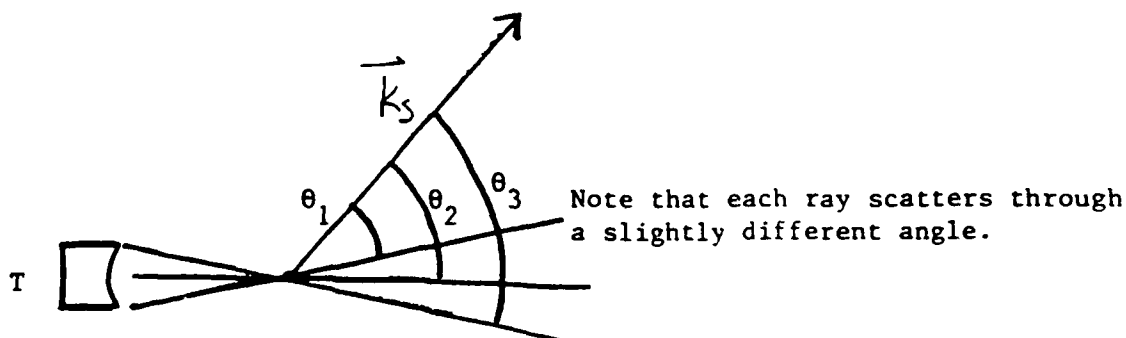


FIG.18. Error due to effective beamwidth

Since the scattering occurs over a range of angles (Fig. 18), an error develops because multiple Doppler shifts are created. This error is related to the effective distribution of angles of the focused beam. For the focused transmitting transducers, the effective distribution of angles is on the order of the radius of the transducer face divided by the focal length. For our apparatus this ratio is $0.5/5.5$ which is equal to 0.09091 radians and is much larger than γ . Therefore an experimentally determined mean axial velocity is not possible from the translational data taken at 0° and 180° .

To optimize the analysis, one should choose a set of two angles (α_* , β_*) such that in one scan experiment K_x is maximized, and in the other experiment K_y is maximized. To find the extremum of K_x , find its derivative with respect to θ_* and set it equal to zero. Therefore

$$\frac{dK_x}{d\theta_*} = \frac{\sqrt{2}}{2}k_0 + \sin(\theta_*) - k_0 \cos(\theta_*) = 0, \text{ and}$$

$$\tan(\theta_*) = \frac{2}{\sqrt{2}}\gamma.$$

Thus, θ_* must be 1.8° or 181.8° . Use of the second derivative test finds that 181.8° is the maximum of the function K_x .

To maximize K_y , follow a similar procedure to get the following relations

$$\frac{dK_y}{d\theta_*} = -\frac{\sqrt{2}}{2}k_0 + \cos(\theta_*) + \frac{\sqrt{2}}{2}k_0 \sin(\theta_*) = 0, \text{ and}$$

$$\tan(\theta_*) = 1/\gamma.$$

Once again, after using the second derivative test, the maximum of K_y is found to be 268.7° .

Thus scanning at the angles $\theta_* = 181.8^\circ$ and 268.7° will give the best results. To determine velocity information from

the variance, skewness, or kurtosis of the translation scans, several scans at 3, 4, or 5 angles respectively, are necessary. A better method is introduced in the next chapter which studies the scattering phenomenon as a function of angle.

APPLICATION OF THE SPECTRAL THEORY TO THE CASE OF VARYING ANGLE AND FIXED SCAN POSITIONS

The second experiment applies the spectral theory to the case of rotating the crossed sound beams at a single scan position. From each 360° scan, turbulent velocity correlations can be determined similarly to the method outlined for translational scans. But to solve a system of 86 equations (one for each angle scanned) in closed form is inefficient. Instead two numerical methods are proposed to derive the velocity information. One is based upon Fourier analysis, and the other is based upon a linear least squares fitting algorithm.

The Fourier method re-interprets the Doppler shift equations for σ^2 , S , K and $\langle f \rangle$ as finite Fourier series. An example of this method (using the variance from Eq. 11) is outlined below:

$$\sigma^2(\theta_*) = K_x^2 \langle V_x^2 \rangle + 2K_x K_y \langle V_x V_y \rangle + K_y^2 \langle V_y^2 \rangle. \quad (11)$$

The quantities K_x^2 , $K_x K_y$, K_y^2 , and σ^2 are all functions of θ_* . However, K_x^2 , $K_x K_y$, and K_y^2 can be written as a finite Fourier series in θ_* without too much difficulty. Start with the K_x^2 expression below:

$$K_x^2 = k_0^2 \left(1 - \frac{\sqrt{2}}{2} \cos \theta_* - \gamma \sin \theta_* \right)^2.$$

This expression can be expanded and regrouped using trigonometric identities to yield:

$$K_x^2 = k_0^2 \left[\left(\frac{5}{4} - \frac{\gamma^2}{2} \right) - \sqrt{2} \cos \theta_* + \left(\frac{1}{4} - \frac{\gamma^2}{2} \right) \cos 2\theta_* - 2\gamma \sin \theta_* + \gamma \frac{\sqrt{2}}{2} \sin 2\theta_* \right]. \quad (21)$$

Similarly, Fourier expressions can be found for $K_x K_y$ and K_y^2 below:

$$K_x K_y = k_{0+}^2 \left[\frac{(\gamma\sqrt{2} + \gamma)}{4} - \gamma \frac{\sqrt{2}}{2} \cos \theta_* + \frac{(\gamma - \gamma\sqrt{2})}{4} \cos 2\theta_* - \frac{\sqrt{2}}{2} \sin \theta_* + \frac{(1 + \gamma^2\sqrt{2})}{4} \sin 2\theta_* \right], \quad (22)$$

$$K_y^2 = k_{0+}^2 \left[\frac{(1 + \gamma^2)}{4} + \frac{(\gamma^2 - 1)}{4} \cos 2\theta_* + \frac{\gamma}{2} \sin 2\theta_* \right]. \quad (23)$$

Thus σ^2 can be rewritten as

$$\begin{aligned} \sigma^2 &= k_{0+}^2 \left[\left(\frac{5}{4} - \frac{\gamma^2}{2} \right) \langle V_x^2 \rangle + 2 \frac{(\gamma\sqrt{2} + \gamma)}{4} \langle V_x V_y \rangle + \frac{(1 + \gamma^2)}{4} \langle V_y^2 \rangle \right] \\ &+ k_{0+}^2 \left[-\sqrt{2} \langle V_x^2 \rangle - 2\gamma \frac{\sqrt{2}}{2} \langle V_x V_y \rangle \right] \cos \theta_* \\ &+ k_{0+}^2 \left[\left(\frac{1}{4} - \frac{\gamma^2}{2} \right) \langle V_x^2 \rangle + 2 \frac{(\gamma - \gamma\sqrt{2})}{4} \langle V_x V_y \rangle + \frac{(\gamma^2 - 1)}{4} \langle V_y^2 \rangle \right] \cos 2\theta_* \\ &+ k_{0+}^2 \left[-2\gamma \langle V_x^2 \rangle - 2\gamma \frac{\sqrt{2}}{2} \langle V_x V_y \rangle \right] \sin \theta_* \\ &+ k_{0+}^2 \left[\gamma \frac{\sqrt{2}}{2} \langle V_x^2 \rangle + 2 \frac{(1 + \gamma^2\sqrt{2})}{4} \langle V_x V_y \rangle + \frac{\gamma}{2} \langle V_y^2 \rangle \right] \sin 2\theta_*, \quad (24) \end{aligned}$$

which is now a Fourier expansion of σ^2 . A Fast Fourier Transform, FFT, can be performed upon the σ^2 data. Although the σ^2 experimental data does not contain 2^n points, which is a prerequisite for performing FFTs, the data repeats every full 360° revolution of the transducers. Therefore, one can expand the data to 2^n points by adding repetitions. Here, n denotes an integer value. From the FFT, one will find the coefficients (a, b, c, d, and e) of σ^2 ,

$$\sigma^2 = a + b \cos \theta_* + c \cos 2\theta_* + d \sin \theta_* + e \sin 2\theta_*, \quad (25)$$

which must be equivalent to the coefficients of the K_x and K_y terms. This is true mathematically using the orthogonal

property of sines and cosines. This sets up the following system of equations:

$$a = k_{0+}^2 \left[\left(\frac{5}{4} - \frac{\gamma^2}{2} \right) \langle V_x^2 \rangle + 2 \frac{(\gamma\sqrt{2} + \gamma)}{4} \langle V_x V_y \rangle + \frac{(1 + \gamma^2)}{4} \langle V_y^2 \rangle \right] \quad (26)$$

$$b = k_{0+}^2 \left[-\sqrt{2} \langle V_x^2 \rangle - 2\gamma \frac{\sqrt{2}}{2} \langle V_x V_y \rangle \right] \quad (27)$$

$$c = k_{0+}^2 \left[\left(\frac{1}{4} - \frac{\gamma^2}{2} \right) \langle V_x^2 \rangle + 2 \frac{(\gamma - \gamma\sqrt{2})}{4} \langle V_x V_y \rangle + \frac{(\gamma^2 - 1)}{4} \langle V_y^2 \rangle \right] \quad (28)$$

$$d = k_{0+}^2 \left[-2\gamma \langle V_x^2 \rangle - 2\frac{\sqrt{2}}{2} \langle V_x V_y \rangle \right] \quad (29)$$

$$e = k_{0+}^2 \left[\gamma \frac{\sqrt{2}}{2} \langle V_x^2 \rangle + 2 \frac{(1 + \gamma^2 \sqrt{2})}{4} \langle V_x V_y \rangle + \frac{\gamma}{2} \langle V_y^2 \rangle \right]. \quad (30)$$

From this system, one can solve to get $\langle V_x^2 \rangle$, $\langle V_x V_y \rangle$, and $\langle V_y^2 \rangle$.

Similar finite Fourier sums have been calculated for $\langle \omega_d \rangle$, $\langle (\omega_d - \langle \omega_d \rangle)^3 \rangle$, and $\langle (\omega_d - \langle \omega_d \rangle)^4 \rangle$. These sums can be interpreted similarly to the variance data to find V_{0x} , V_{0y} , $\langle V_x^3 \rangle$, $\langle V_x^2 V_y \rangle$, $\langle V_x V_y^2 \rangle$, $\langle V_y^3 \rangle$, $\langle V_x^4 \rangle$, $\langle V_x^3 V_y \rangle$, $\langle V_x^2 V_y^2 \rangle$, $\langle V_x V_y^3 \rangle$, and $\langle V_y^4 \rangle$.

The other method of finding the velocity correlations uses an algorithm known as the method of least squares². This procedure involves fitting a function F to the experimental data. Adjustable parameters of the function F are determined by minimizing an error function, E , as described in the following example:

In Equation 11, the variance, σ^2 , is defined as:

$$\sigma^2(\theta) = K_x^2 \langle V_x^2 \rangle + 2K_x K_y \langle V_x V_y \rangle + K_y^2 \langle V_y^2 \rangle.$$

$$\text{Let } f(\theta) = K_x^2(\theta)$$

$$g(\theta) = 2K_x K_y(\theta)$$

$$h(\theta) = K_y^2(\theta)$$

$$a = \langle V_x^2 \rangle$$

$$b = \langle V_x V_y \rangle$$

$$c = \langle V_y^2 \rangle$$

$$\text{and } F(a, b, c, \theta) = af(\theta) + bg(\theta) + ch(\theta).$$

The error function is $E = \sum_{\text{all data pts}} \{\sigma^2 - F\}^2$. (31)

Now the adjustable parameters in this problem are the velocity correlations a , b , and c . If they are chosen appropriately, the error function will be a minimum. This means that the calculated velocity correlations are the values the theory predicts for that data.

To find the minimum errors, find the minimum of E with respect to a , b , and c .

The minimum for a is

$$\begin{aligned} \frac{\partial E}{\partial a} &= (\sum \partial \{\sigma^2 - F\}^2) / \partial a \\ &= \sum 2\{\sigma^2 - F\}(-f(\theta)). \end{aligned} \quad (32)$$

Set derivative equal to zero to find extrema

$$\begin{aligned} \sum f(\theta)\sigma^2 &= \sum f(\theta) F \\ &= a \sum f^2(\theta) + b \sum f(\theta)g(\theta) + c \sum f(\theta)h(\theta). \end{aligned} \quad (33)$$

Similarly the minima of b and c yield the relations

$$\sum g(\theta)\sigma^2 = a \sum f(\theta)g(\theta) + b \sum g^2(\theta) + c \sum g(\theta)h(\theta), \quad (34)$$

$$\sum h(\theta)\sigma^2 = a \sum f(\theta)h(\theta) + b \sum g(\theta)h(\theta) + c \sum h^2(\theta). \quad (35)$$

Eqs. 33, 34, and 35 yield the following system of equations:

$$C_{f\sigma} = a B_{ff} + b B_{fg} + c B_{fh} \quad (36)$$

$$C_{g\sigma} = a B_{fg} + b B_{gg} + c B_{gh} \quad (37)$$

$$C_{h\sigma} = a B_{fh} + b B_{gh} + c B_{hh}, \quad (38)$$

where

$$C_{f\sigma} = \sum K_x^2(\theta)\sigma^2$$

$$\begin{aligned}
C_{g\sigma} &= \sum 2K_x K_y(\theta) \sigma^2 \\
C_{h\sigma} &= \sum K_y^2(\theta) \sigma^2 \\
B_{ff} &= \sum K_x^2(\theta) K_x^2(\theta) \\
B_{fg} &= \sum 2K_x^2(\theta) K_x K_y(\theta) \\
B_{fh} &= \sum K_x^2(\theta) K_y^2(\theta) \\
B_{gg} &= \sum 4K_x K_y(\theta) K_x K_y(\theta) \\
B_{gh} &= \sum 2K_x K_y(\theta) K_y^2(\theta) \\
B_{hh} &= \sum K_y^2(\theta) K_y^2(\theta) .
\end{aligned} \tag{39}$$

This system of equations can be solved by Gauss-Jordan row reduction which is easily handled by a computer. The computer routine to perform Gauss-Jordan reduction has been written for the Macintosh II by the author. This program is listed in Appendix C.

REYNOLDS NUMBER SIMILARITY IN TURBULENT FLOW

In Townsend's classic text, The Structure of Turbulent Shear Flow,⁹ on page 89 he points out

"that a turbulent flow, suitably defined by boundary conditions, has a main structure that is independent of the fluid viscosity, provided that it is not too large."

He adds

"... geometrically similar flows are similar at all sufficiently high Reynolds numbers..."

Finally, Townsend states the principle of Reynolds number similarity,

"In a fully turbulent flow, there exists a region including almost all the flow, over which the direct action of viscosity on the mean flow is negligible, ..."

Commenting that the Reynolds stresses are large compared with the mean viscous stresses, he states that the energy-containing components of the turbulence are determined by the boundary conditions of the flow alone and are independent of the fluid viscosity.

We have made use of this fact in our project. Wygnanski¹² studied turbulent flow in air at Reynolds numbers on the order of $Re \approx 10^5$. Thus, his data can be compared to our own. From fits and trends in our data, we will be able to decide how well we predict turbulent flows. Wygnanski's results are considered the standard of measurement for turbulent jet flow in air. Thus, if we can show results similar to his, we will have succeeded in proving our method actually measures turbulent velocities. However,

we should encounter differences in the higher order correlation functions because the physical make-up of the jet used by Wygnanski and the one used in the scattering experiment is different. Wygnanski uses a simple nozzle (of diameter 1.04 inches) to generate turbulent shear flow in a large open space. Our submerged water jet has a large circular disk (of diameter equal to 6 inches) encompassing the 1/4 inch nozzle and is placed in a one cubic meter tank. Unfortunately the tank is not large enough to avoid interfering with the entrainment of the flow on the skirts of the jet. This setup was unavoidable due to size constraints of our laboratory and tank availability.

EXPERIMENTAL RESULTS

A. Description of the Spectral Analysis Measurements

The results of this experiment present the calculated velocity distributions across the width of the turbulent water jet. The process by which measurements of the nonlinearly scattered sum frequency intensity spectra are used to obtain the turbulent velocity correlations involves several computational steps that are explained next. Translational and rotational data analysis involve similar discussions. Therefore a single general discussion is presented for both cases.

It is pointed out that spectra (measured on the Tektronix 7L5 sweep spectrum analyzer) are a detection of the sum frequency tone that changes its frequency as a function of time. Therefore, one must average the results of many spectral sweeps in order to obtain a true time average spectrum. The IQ400 digital oscilloscope accomplishes this task by signal averaging the output voltage from 20 sweeps versus time. The output voltage is proportional to the rms pressure amplitude in the spectrum. The sweep time base is proportional to the frequency in the spectrum. The average rms spectrum is then saved on a 3.5 inch floppy disk. From voltage and time base calibrations the average rms spectrum is converted to an intensity spectrum as a function of frequency. The averaged spectra for several angles are shown in Figs. 19a and 19b. Each spectrum was obtained with the overlap region fixed upon the jet axis.

The translational scattering experiments (at fixed angle) involved scanning the overlap region at 40 scan positions across the jet over the range $x = \pm 2$ inches. The angular scattering experiments are performed at 80 individual angles at each scan position. Angular scattering was performed at 11 different scan positions between $x=0$ and $x= 2.0$ inches. The entire crossed beam scattering experiment involved 880 time averaged spectra.

B. Angular Scattering Results

The graphs of the total intensity $I_+(\theta_*)$, Doppler shift $f_d = \langle f \rangle - f_{0+}$, variance σ^2 , skewness S , and kurtosis K are presented as a function of angle θ_* for the interaction region located on the jet axis (Figs. 20 -24). The calculations for the spectral moments for the average spectrum are obtained by a computer analysis. An Apple IIe Basic program called "Analyzer" is used to analyze the translational scans and a Turbo Pascal program called "Mac" is used for the angular scattering trials. These programs converted the rms voltage spectra to intensity spectra and then found the spectral moments. These programs are listed in Appendix C.

In order to obtain the required velocity correlations, the values from the spectral moments $\langle f \rangle$, $\langle (f - \langle f \rangle)^2 \rangle$, $\langle (f - \langle f \rangle)^3 \rangle$, and $\langle (f - \langle f \rangle)^4 \rangle$ are numerically curve fit using the linear least squares fit algorithm that was outlined on pages 32 - 33. The results for the Doppler shift, f_d , are shown in Fig. 21. The results for the variance, σ^2 , (or second moment) along the third and fourth moments are shown in Figs. 22, 25 and 26, respectively.

Results for determining the mean velocity components, V_{0x} and V_{0y} , involve measurements of the Doppler shift, $f_d = (\langle f \rangle - f_{0+})$ across the jet. These velocities (shown in Figs. 27 and 28) are plotted versus the normalized scan position η , which is given by x / y . Here, the scan position is located at the distance $y = 33.9 d$ from the nozzle exit, where d is the nozzle diameter.

Pitot tube measurements (of the axial mean flow velocity profile across the jet) obtained in the laboratory are used to determine the accuracy of the nonlinear scattering method. A comparison of the pitot tube measurements of V_{0y} across the jet with the rotational scattering experiment's determination of V_{0y} is shown in Fig. 27. On axis, where $\eta = 0$, the pitot tube maximum axial velocity, U_m , is 1.187 m/s. For comparison, the

the scattering experiment yielded a value of $U_m = 1.22 \pm 0.01$ m/s. These profiles of the axial mean flow are in agreement with each other and with Wygnanski's¹² published data (not shown) for a similar jet flow involving a turbulent air jet.

The radial mean velocity distribution V_{0x} is shown in Fig. 28. This velocity profile is theoretically obtained by inserting the axial mean velocity V_{0y} into the equation of continuity for mean flow. Notice that V_{0x} is on the order of 10^{-2} times less than V_{0y} , making it difficult to predict V_{0x} from experimental scattering data. Pitot tube measurement of the radial flow are not possible.

The second set of graphs are related to the rms velocity distributions. Since translational scattering data and pitot tube measurements are unable to obtain the higher order correlations, Wygnanski's data¹² is used to make comparisons with the rotational measurements of the rms velocities. The predictions for the second order correlation $\langle V_x^2 \rangle$ (Fig. 29) matched well with Wygnanski's data. Wygnanski's jet, however, does not have the 6 inch diameter plate surrounding its nozzle. This might account for the reason our radial variations are broader. The other two second order velocity correlations $\langle V_x V_y \rangle$ and $\langle V_y^2 \rangle$ (shown in Figs. 30 and 31), followed the same general trend as Wygnanski, but the results shown here indicate a subtle difference between his jet's construction and ours.

The third order velocity correlation coefficients are presented in Figs. 32-35. These values, determined from the rotational runs, are compared with some of Wygnanski's data. In Fig. 33, it is observed that both sets of plots for $\langle V_x^3 \rangle$ agree in magnitude and trend. This is also true for the results of $\langle V_x^2 V_y \rangle$ that are shown in Fig. 32. However, a discrepancy arises with the $\langle V_x V_y^2 \rangle$ profile of Fig. 32 which indicates that the differences in his jet and ours is noticeable at higher order velocity correlations.

The fourth order velocity correlations are presented in Figs. 36 and 37. These correlations are a triumph of the project

because, to the author's knowledge, no one else to date has been able to measure them reliably. Since there are no published fourth order relations to compare with our jet, we cannot make any comparisons. Structure can be observed in the functions. This indicates that the apparatus is sensitive to fourth order fluctuations.

The last graphs shown in Figs. 38 and 39 depict the variations in turbulent intensity across the jet. One defines the turbulent intensity to be the ratio of the rms fluctuating motion in a specified direction to the mean flow measured at that point. The intensity profiles show the dramatic increase in turbulent rms velocity off axis. These results indicate that the flow becomes increasingly random off axis.

C. Translational Scanning Results

Nonlinear scattering experiments that are performed at a fixed angle, while the interaction region scans across the width of the jet, are called translation scans. For the experiments involving translation scans at fixed angle (forward scattering at 0° and back scattering at 180°). Predictions for the radial and axial mean velocity components, V_{0x} and V_{0y} can be obtained by measuring the average frequency $\langle f \rangle$ vs scan position (and subsequently the Doppler shift $f_d = \langle f \rangle - f_{0+}$) and directly inserting these results into the closed form solutions given by Eqs 19 and 20. The Doppler shift as a function of scan position η (for $\theta_s = 0$ and $\theta_s = 180$) are shown in Fig 40 and 41, respectively. These Doppler results are used in Eq. 19 to predict the radial mean flow velocity profile, $V_{0x}(\eta)$, that is shown in Fig. 42.

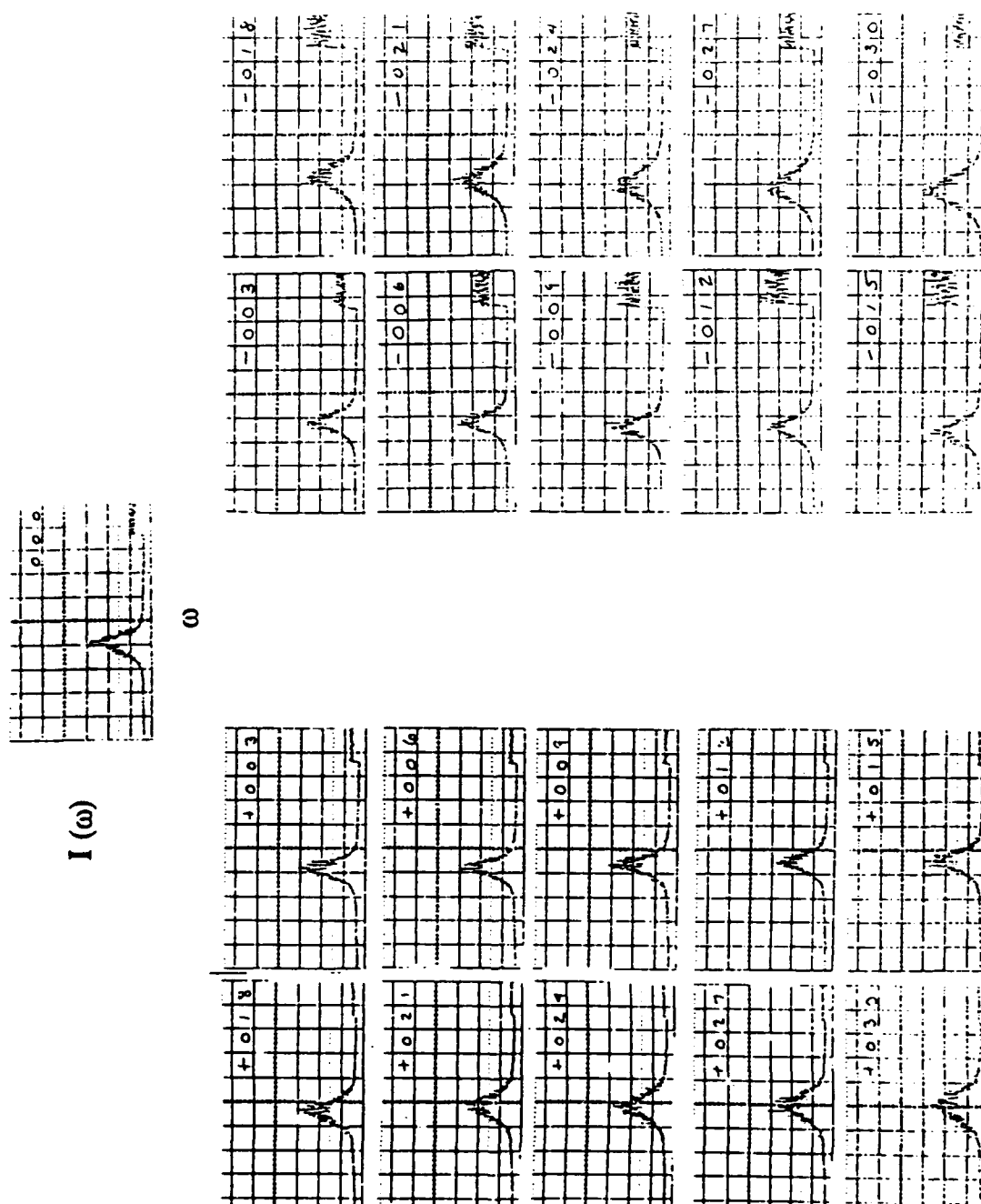


FIG. 19a. Sum frequency spectra for angles between -30 and 30 degrees

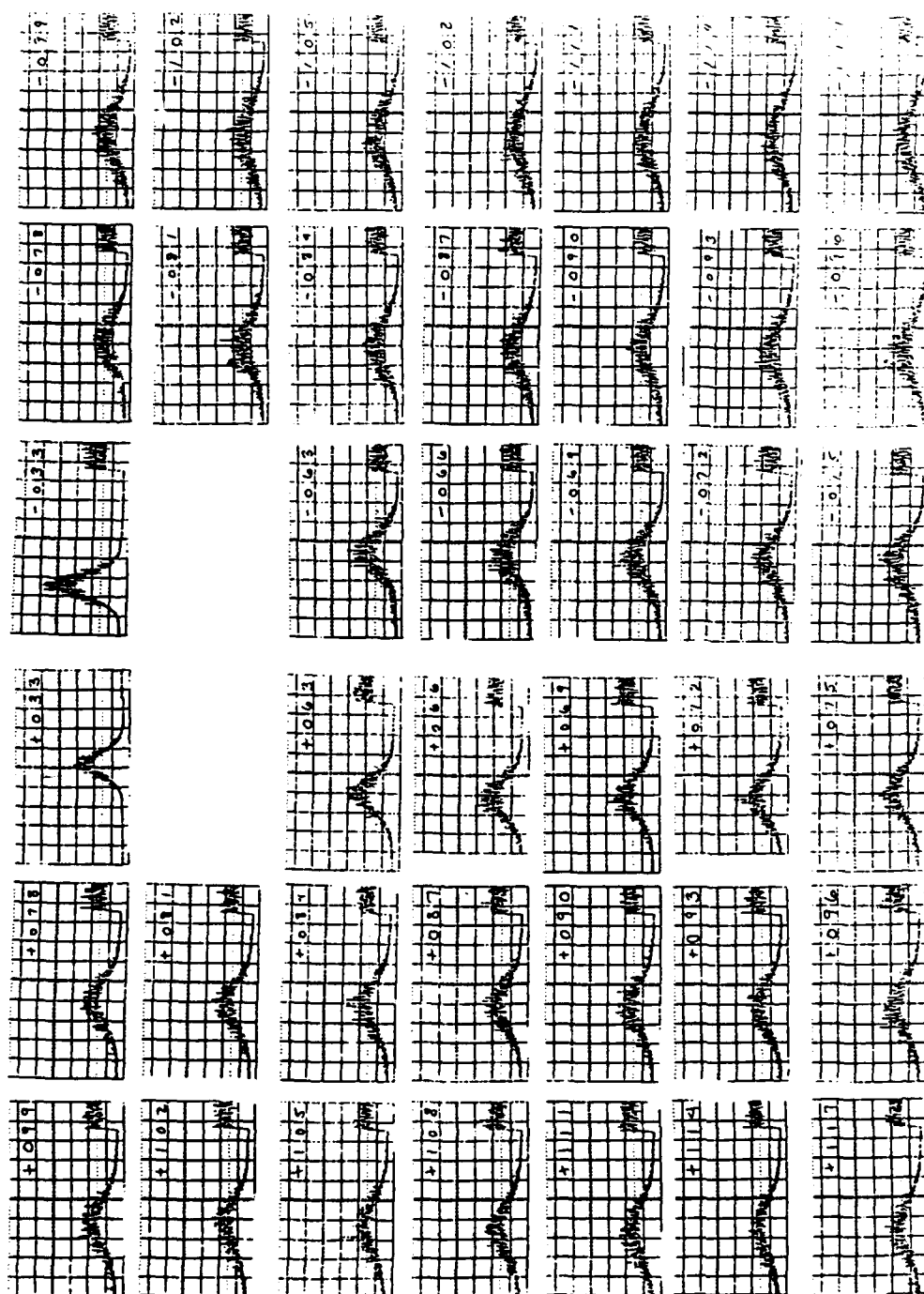


FIG. 19b. Sum frequency spectra for angles -117 to -30 degrees and 30 to 117 degrees

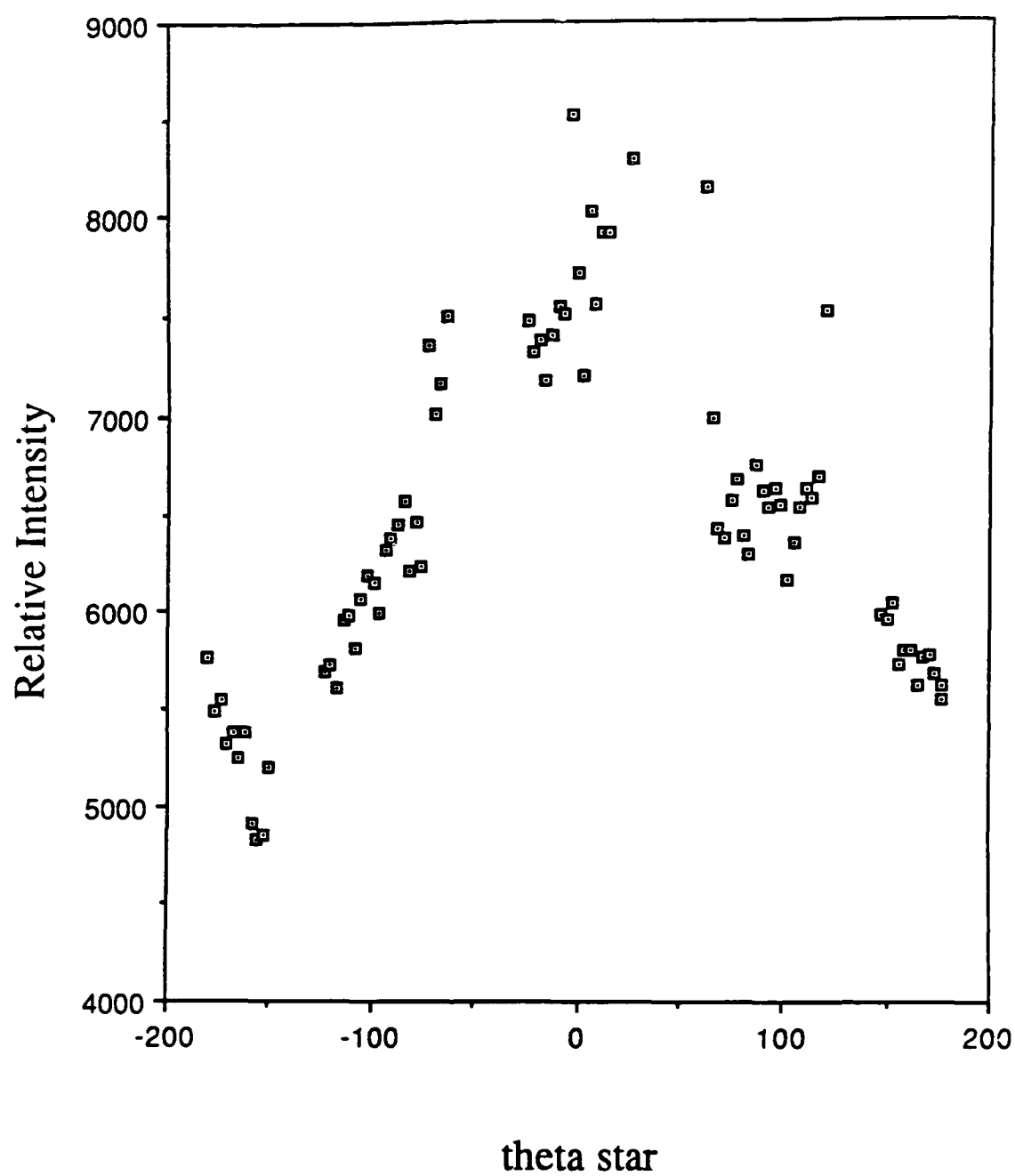


FIG. 20. Relative Intensity vs. theta star

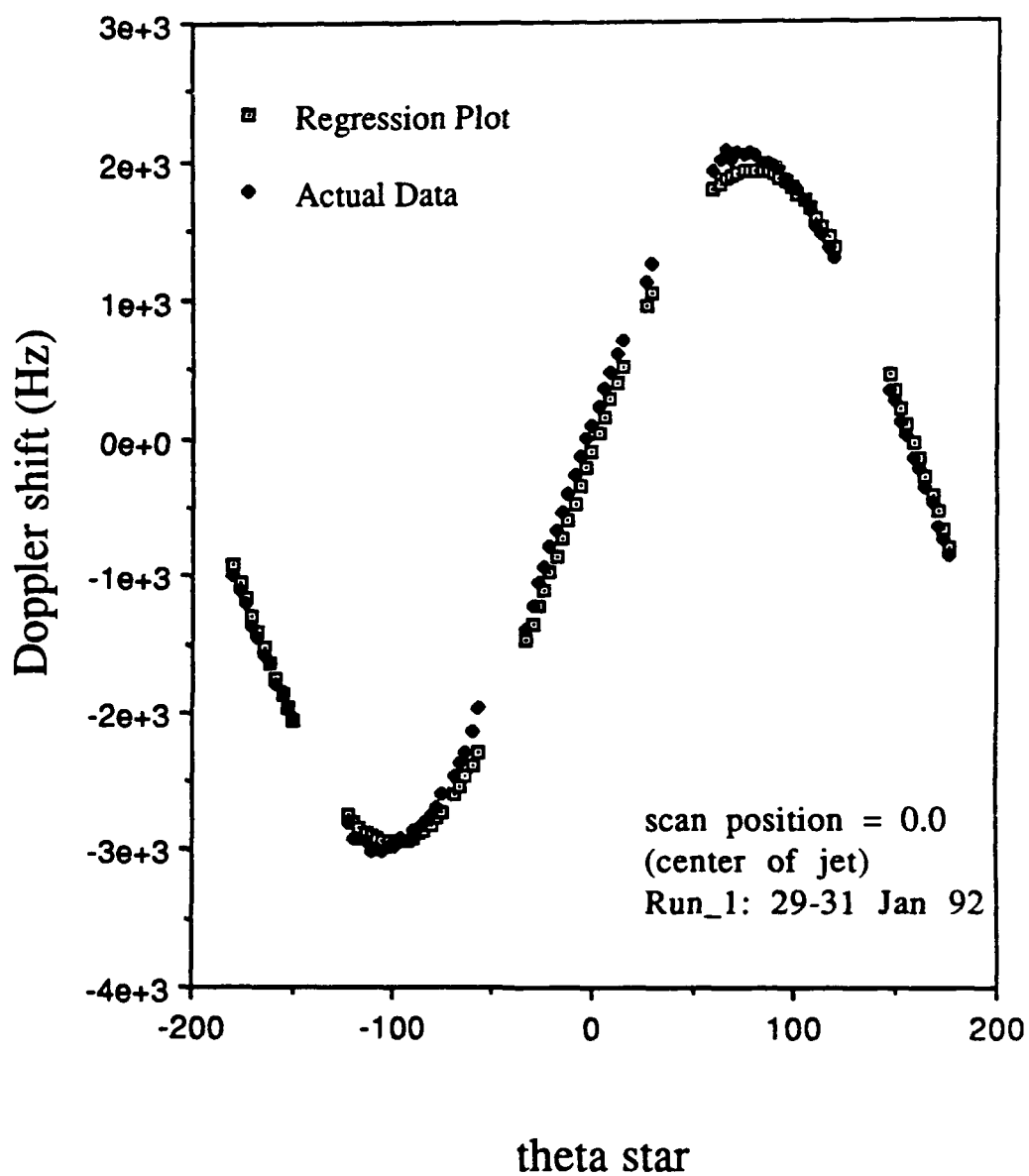


FIG. 21. Regression plot of the average Doppler shift

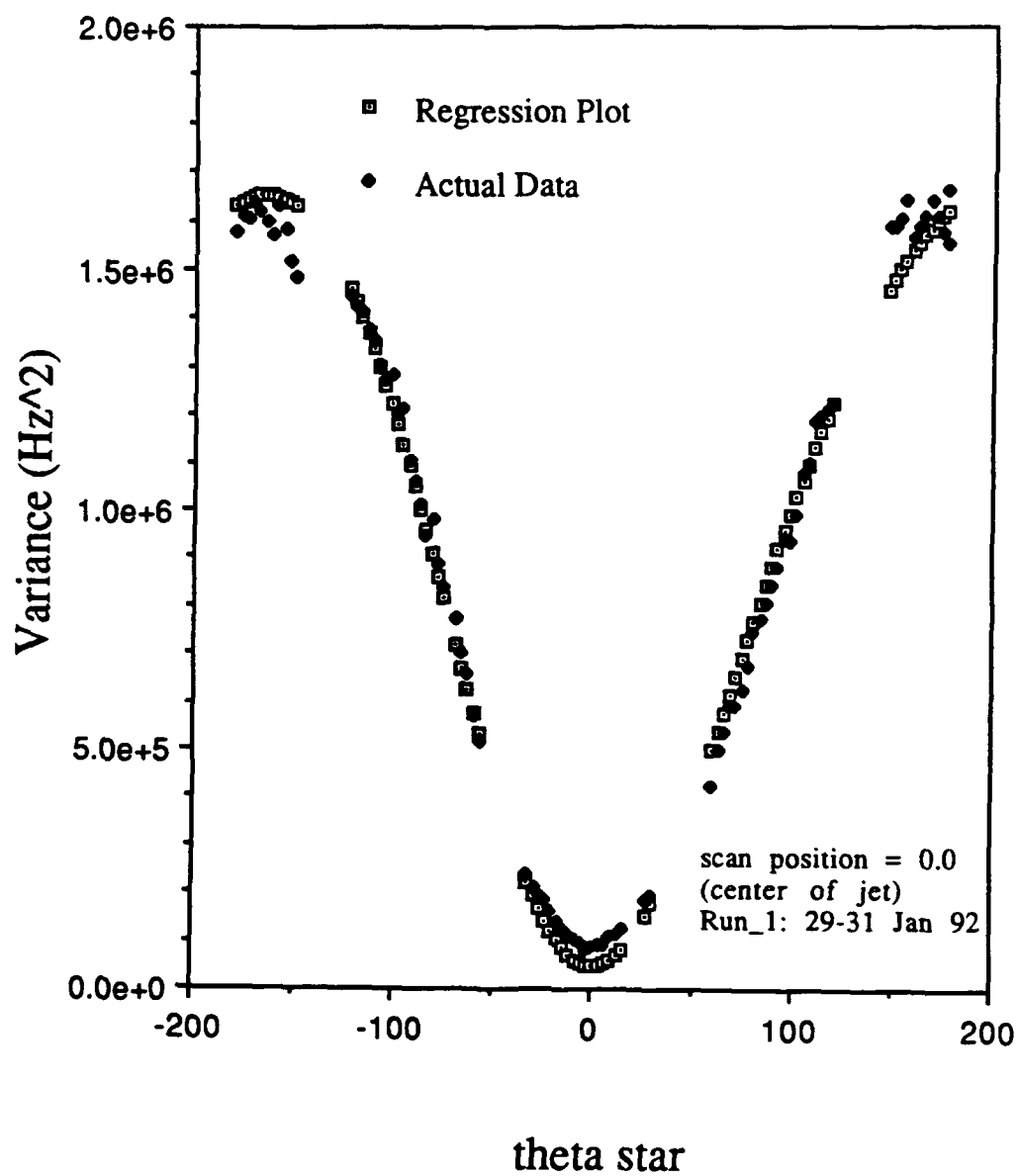


FIG. 22. Regression plot of the variance

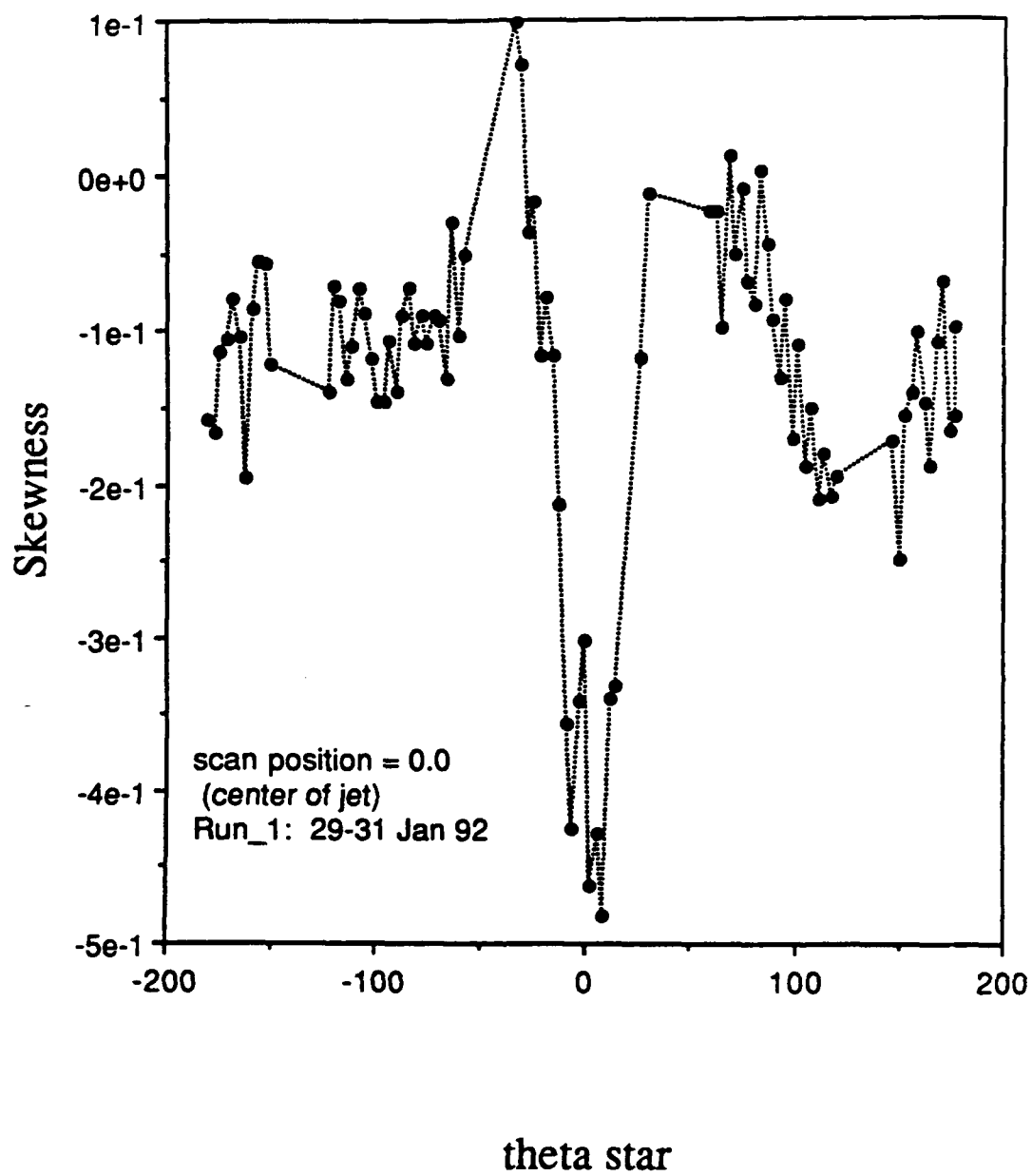


FIG. 23. Skewness vs. theta star

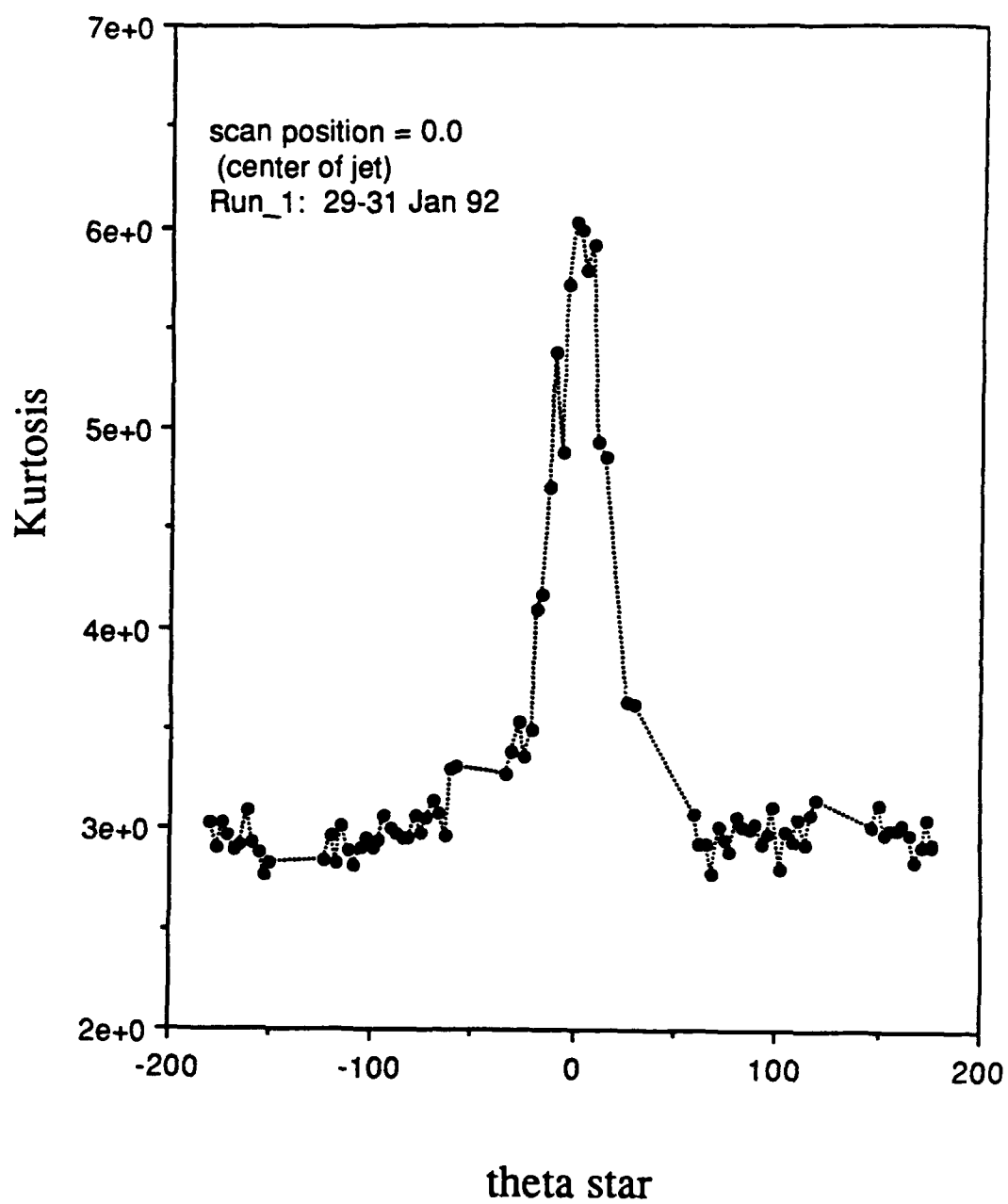


FIG. 24. Kurtosis vs. theta star

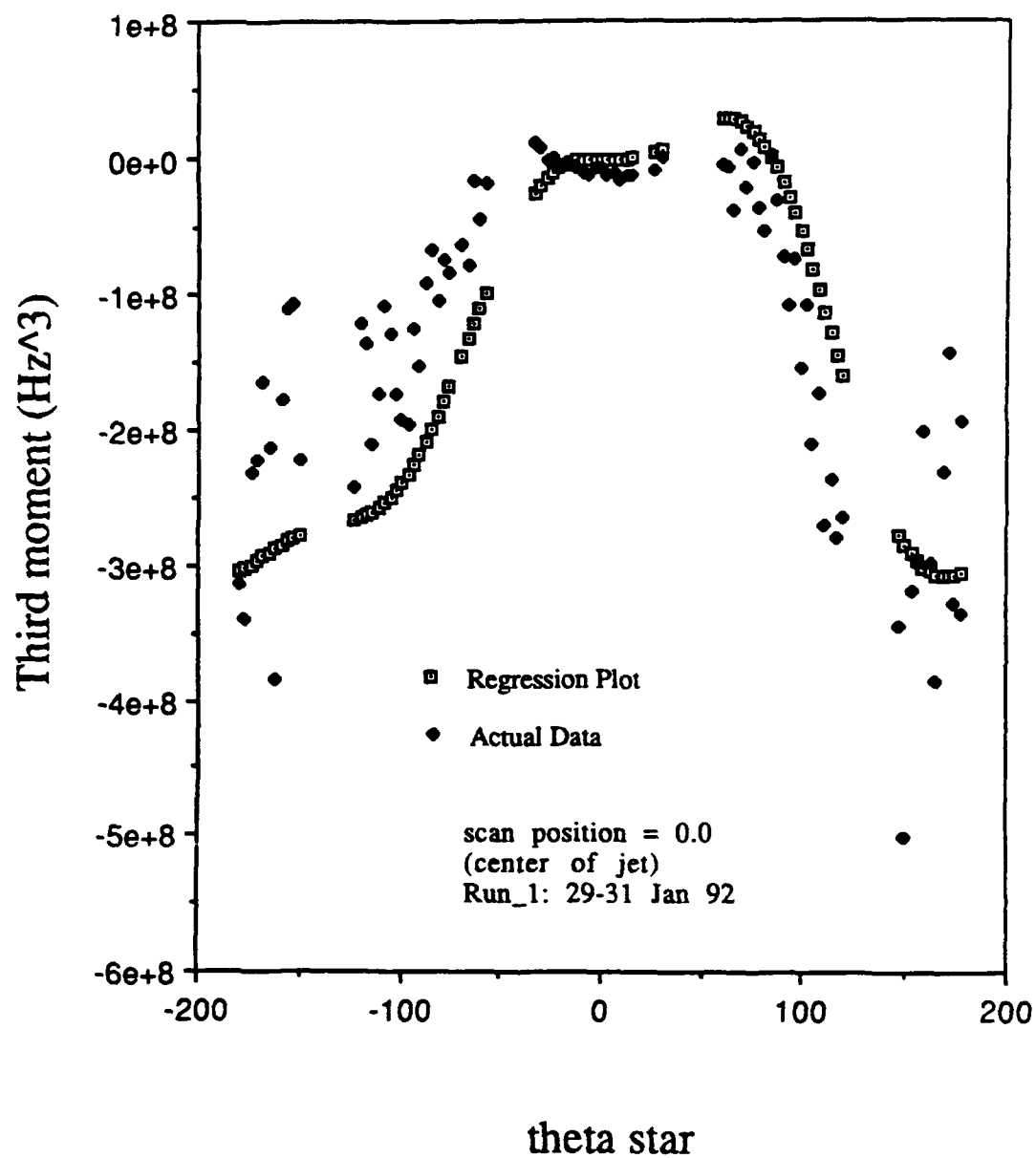


FIG. 25. Regression plot of the third moment

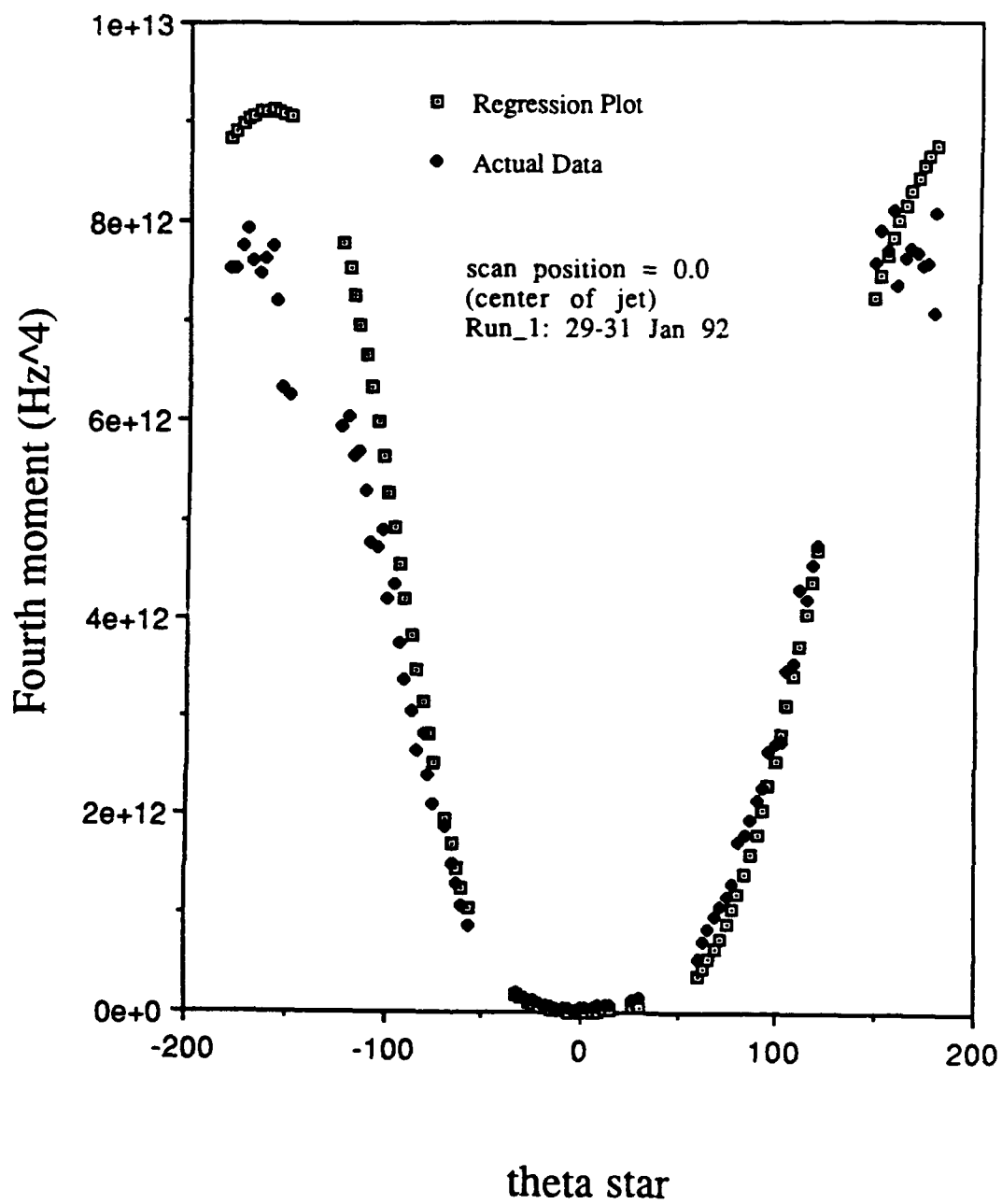
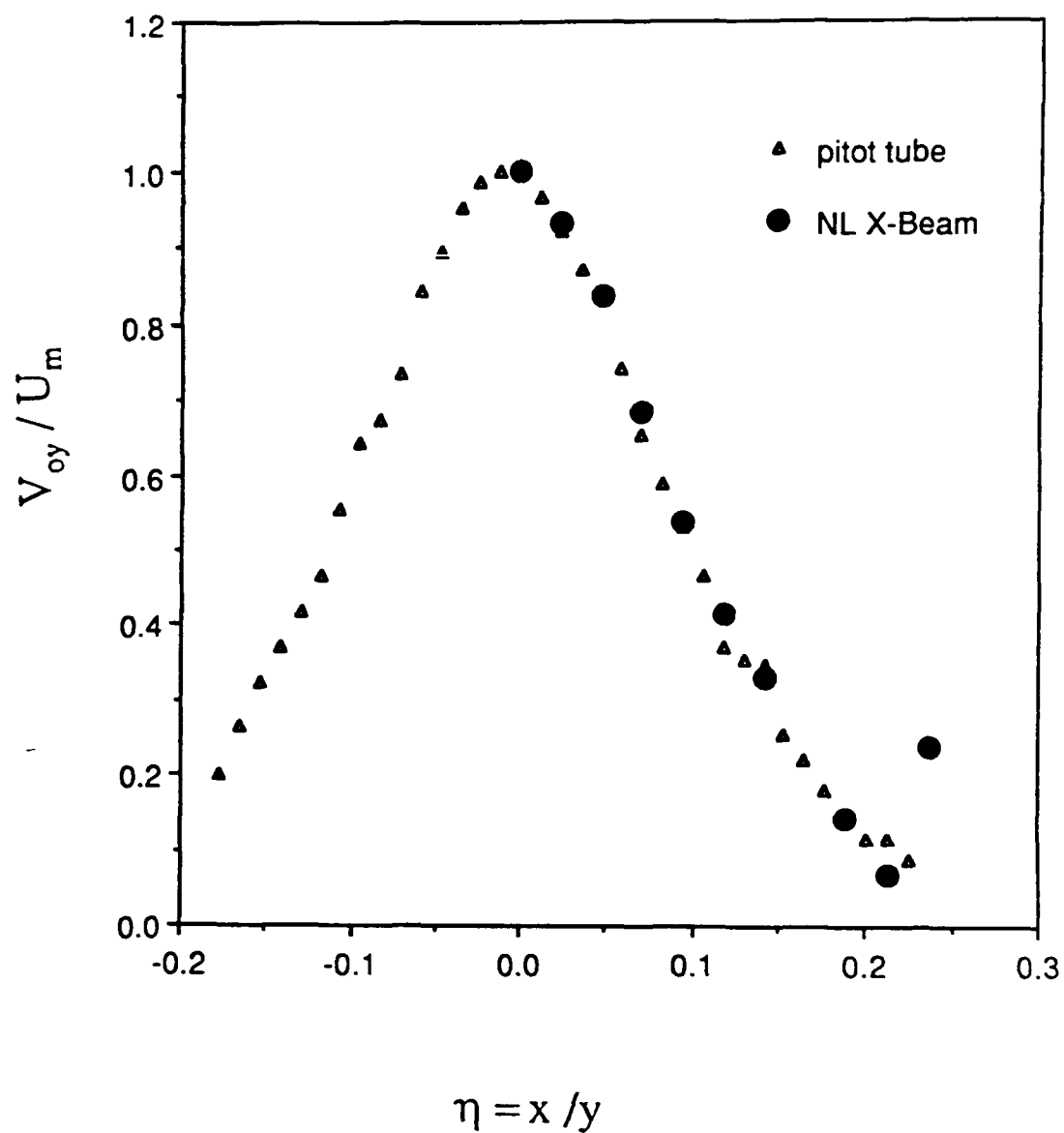


FIG. 26. Regression plot of the fourth moment



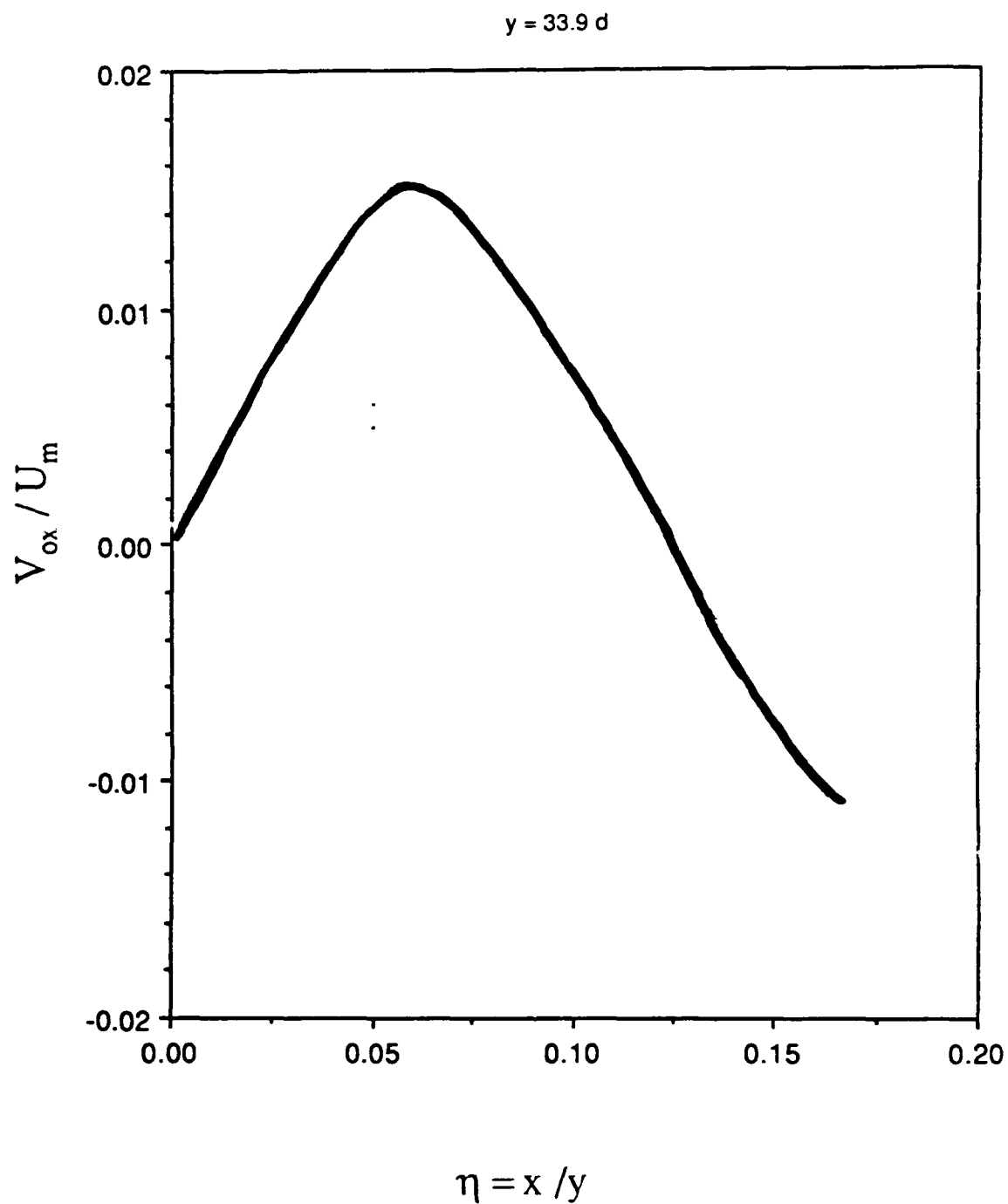


FIG. 28. Mean radial velocity obtained from the continuity equation

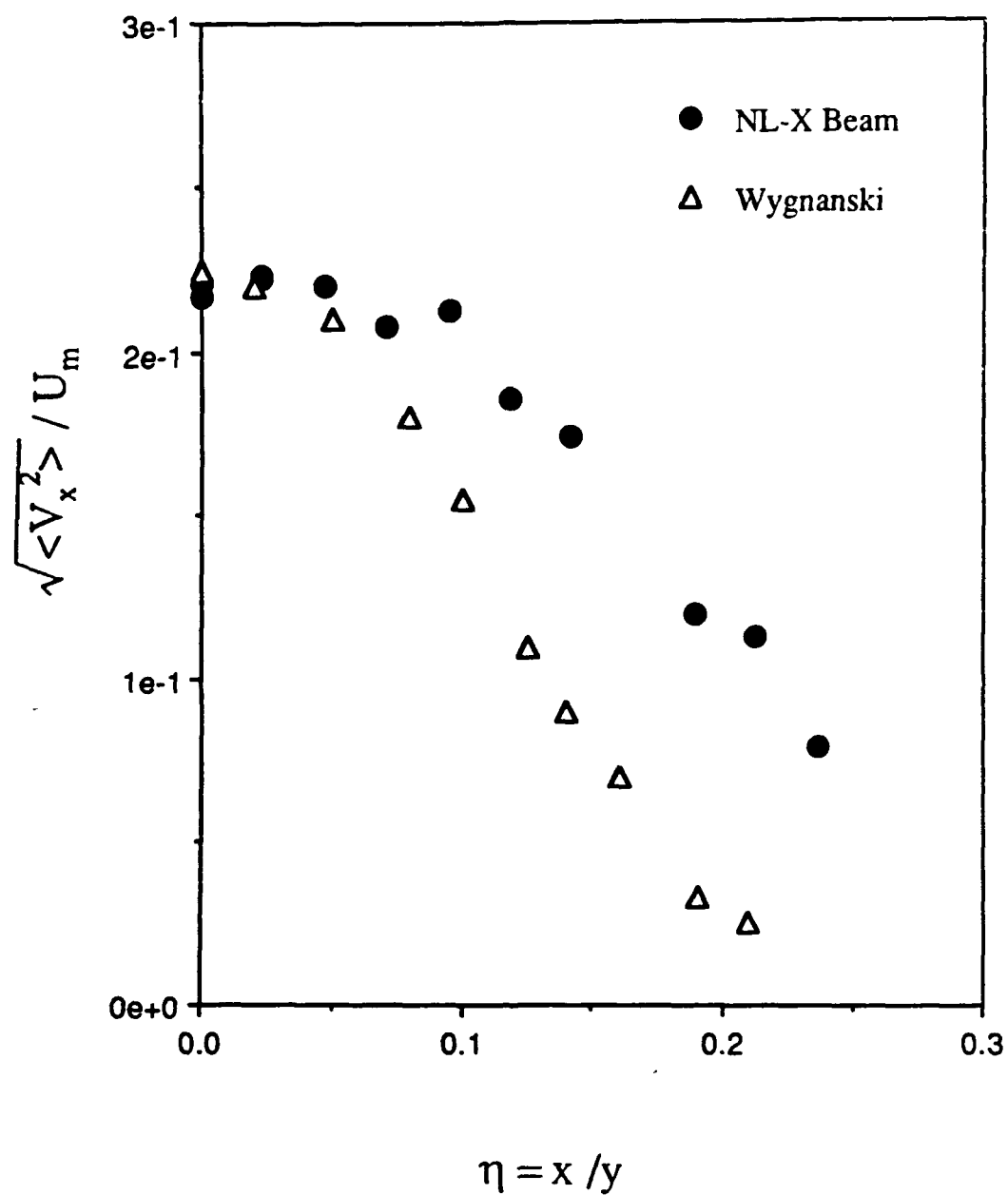


FIG. 29. Comparison of Wygnanski's data to NL X-Beam data (rotational) for the radial rms velocity across the jet

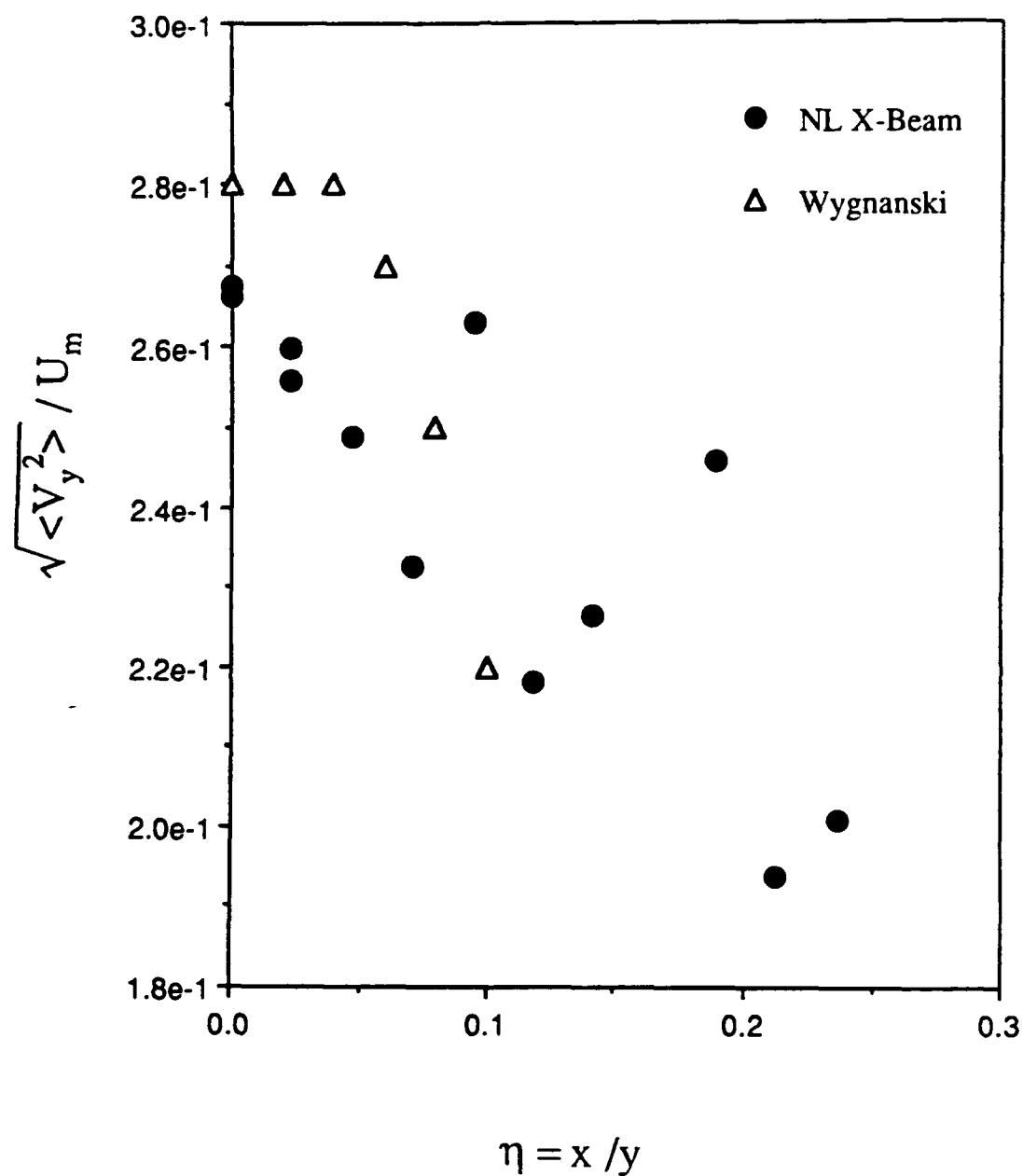


FIG. 30. Comparison of Wygnanski's data to NL X-Beam data (rotational) for the rms axial velocity across the jet

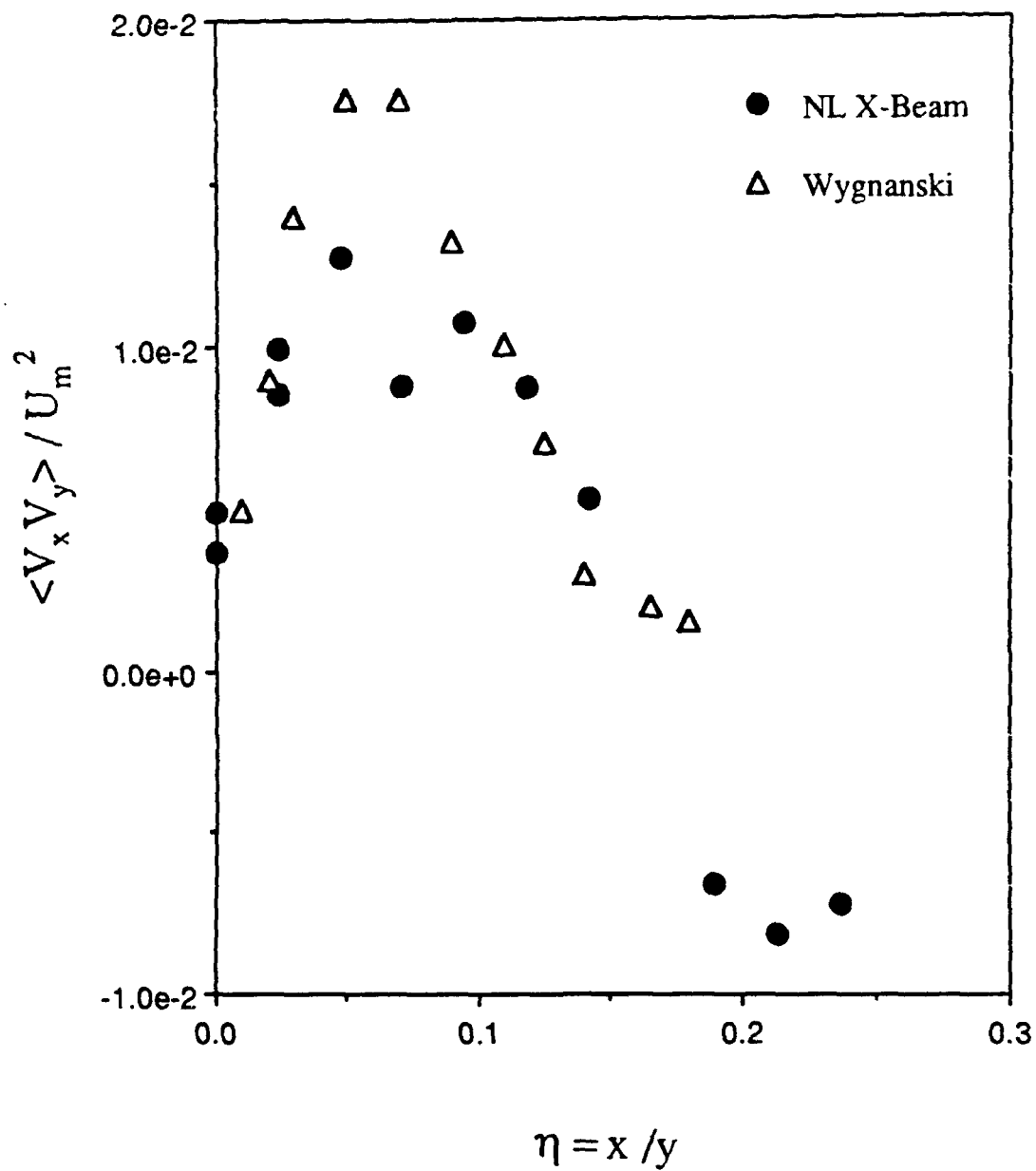


FIG. 31. Comparison of Wynanski's data to NL X-Beam data (rotational) for the Reynolds shear stress across the jet

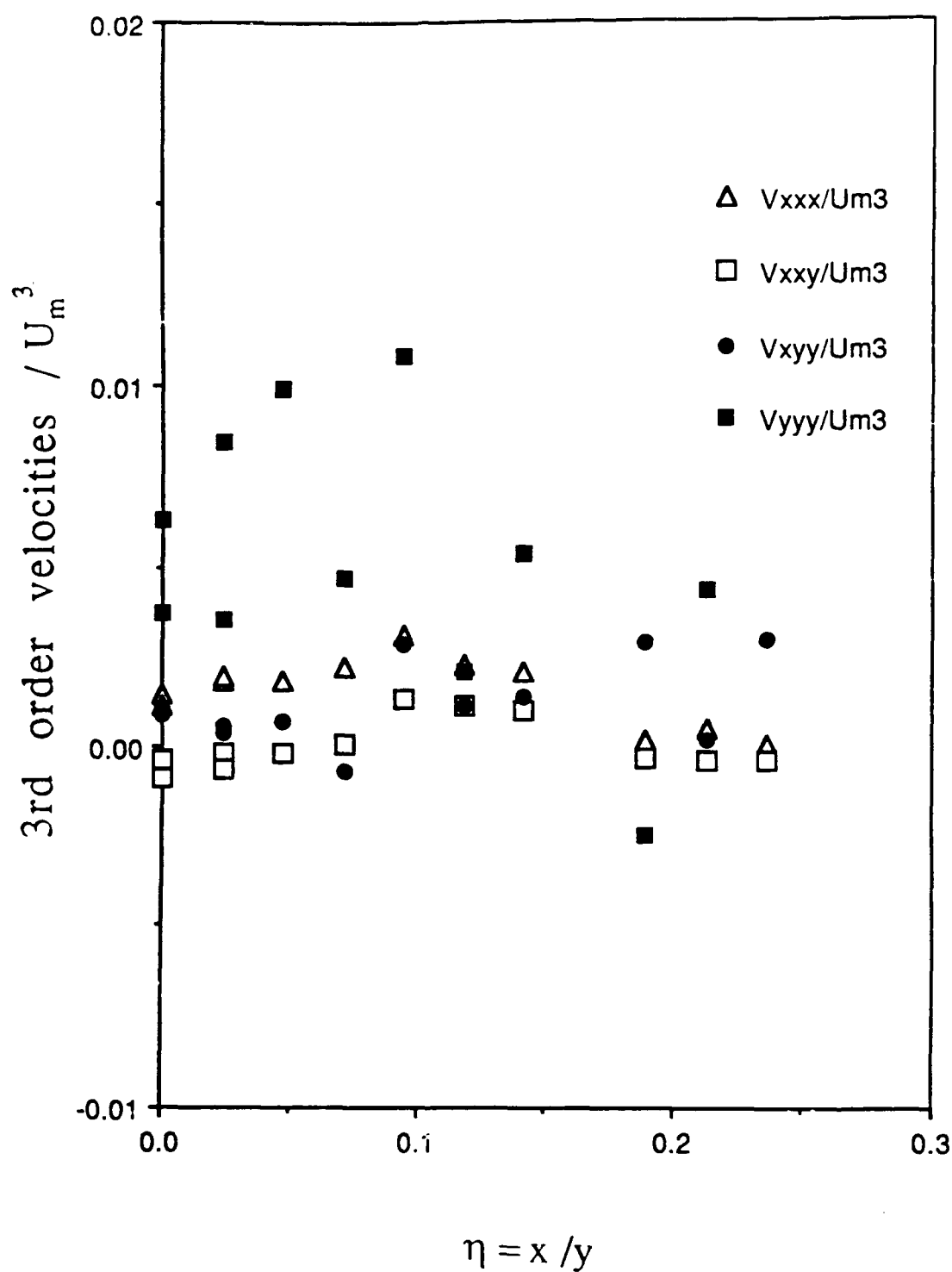


FIG. 32. Triple Velocity Correlations

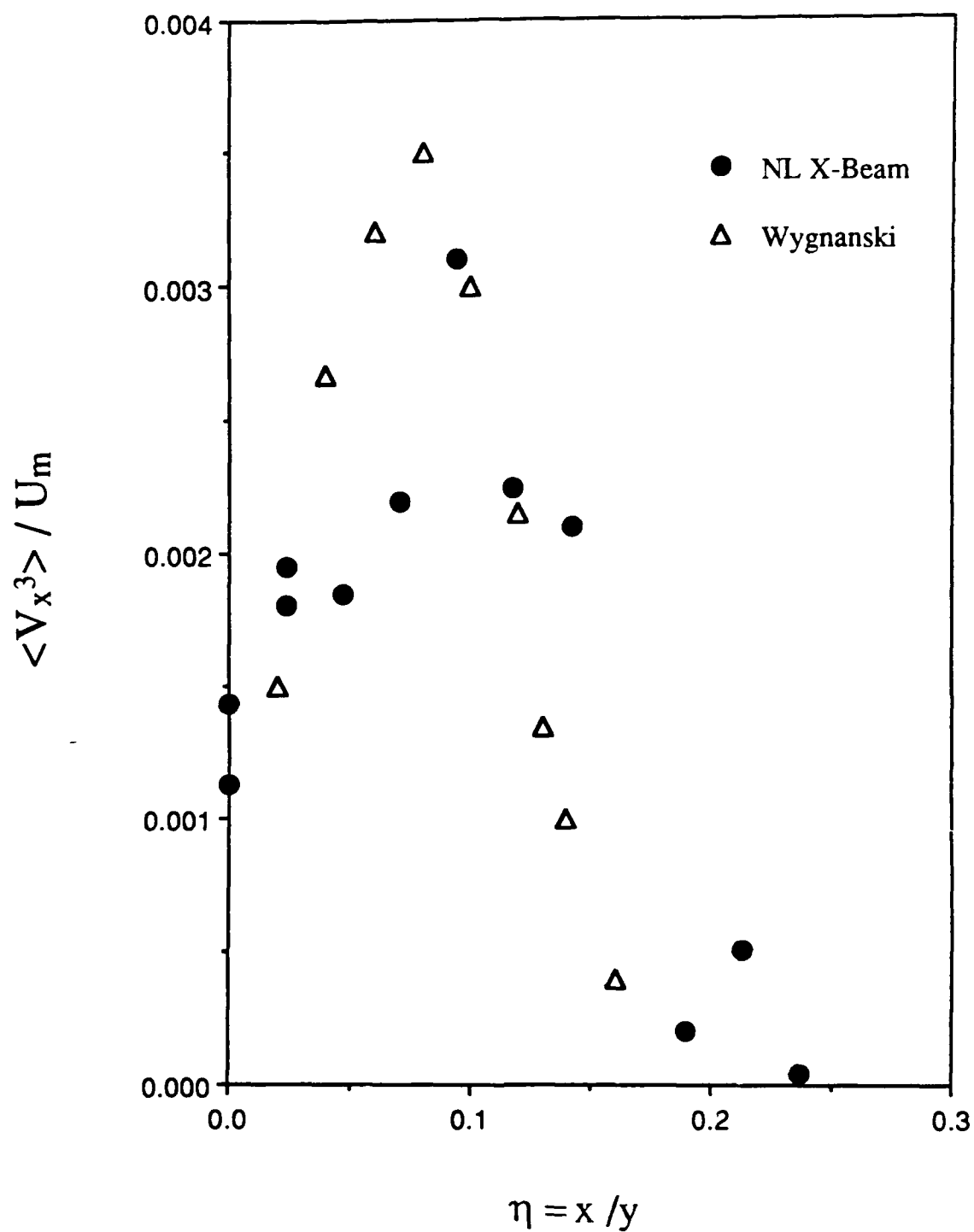


FIG. 33. Comparison of Wygnanski's data to NL X-Beam data (rotational) for the third order radial velocity component

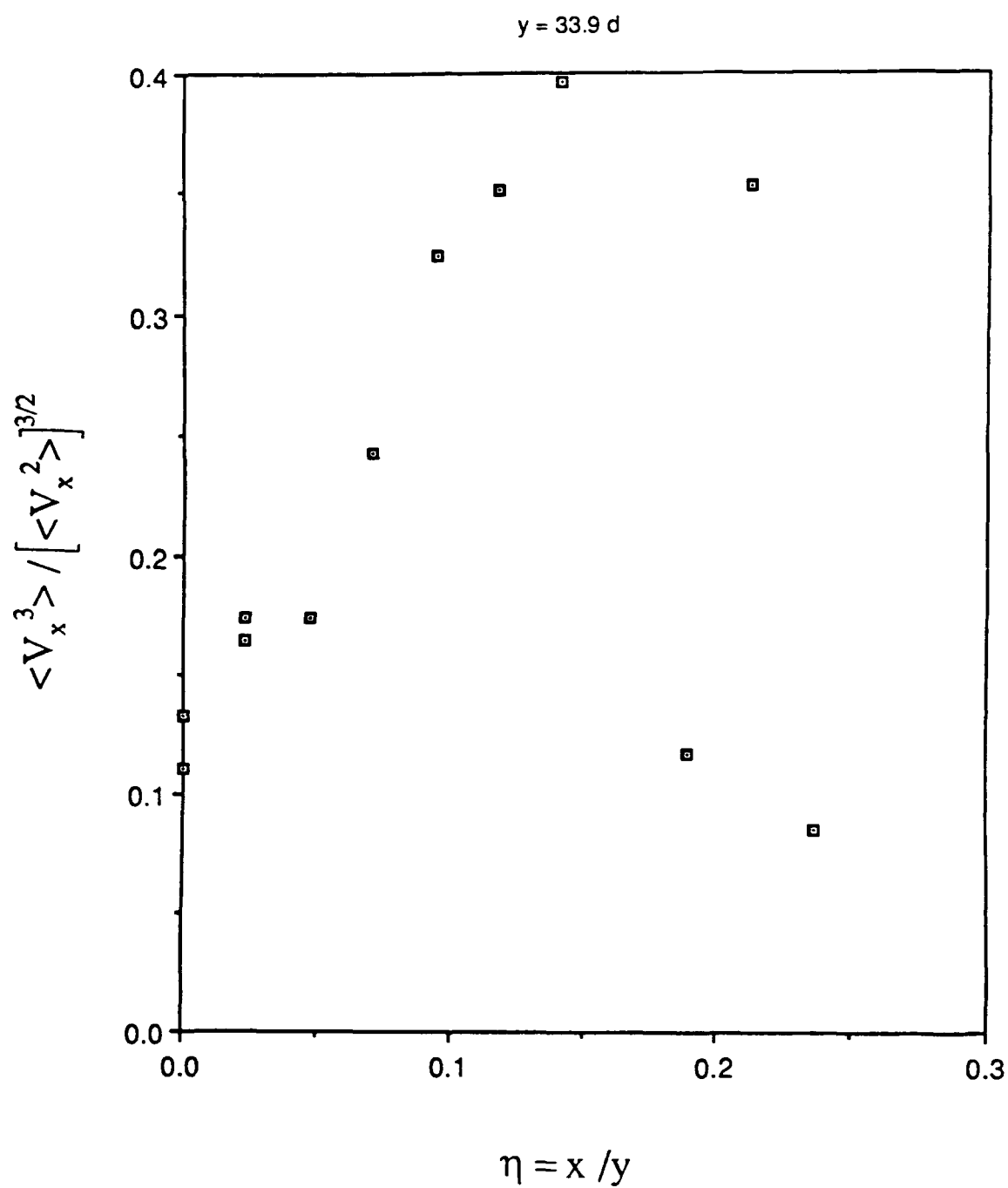


FIG. 34. Triple velocity correlation coefficient (radial) across the jet

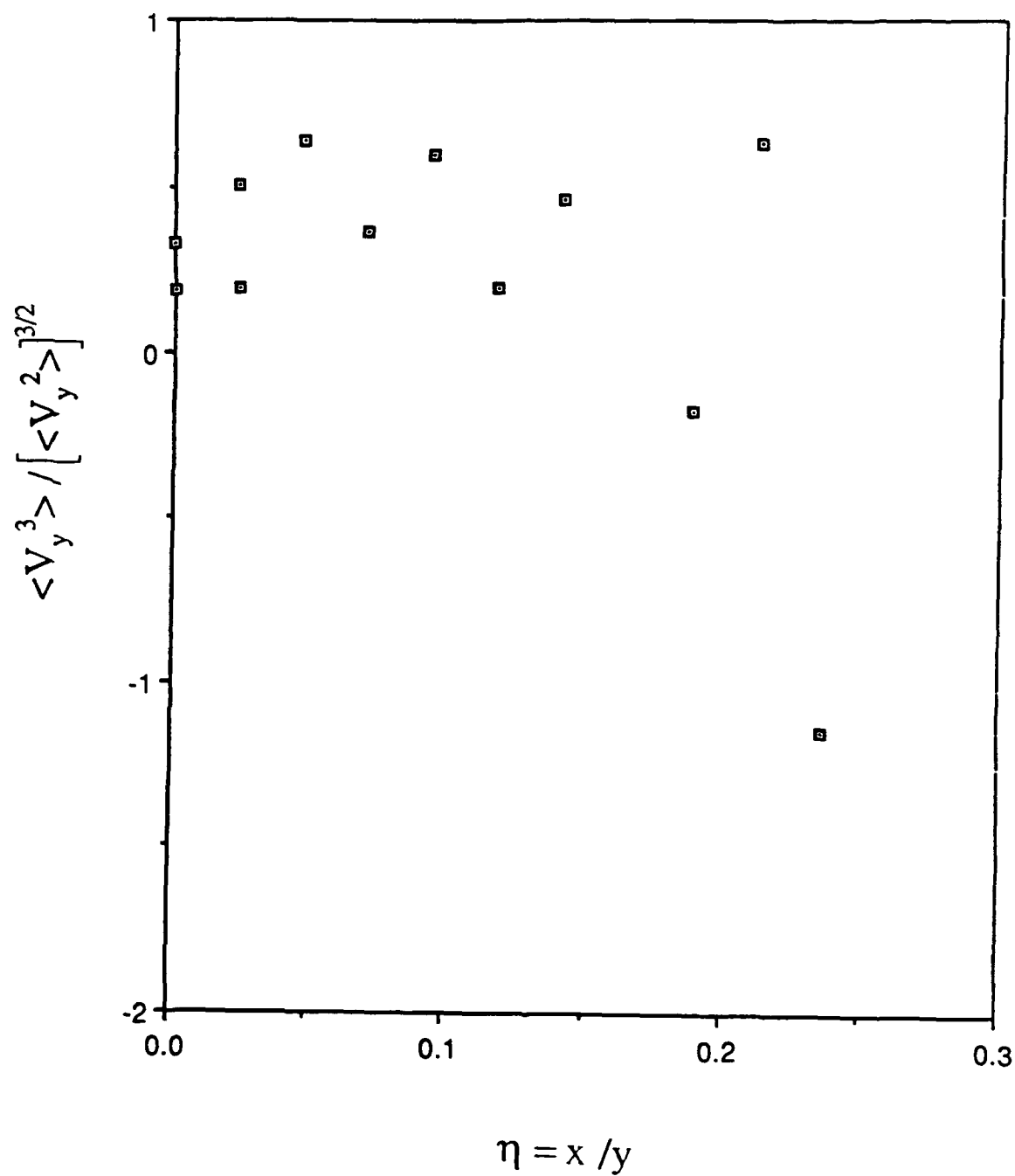
$y = 33.9 d$ 

FIG. 35. Triple velocity correlation coefficient (axial) across the jet

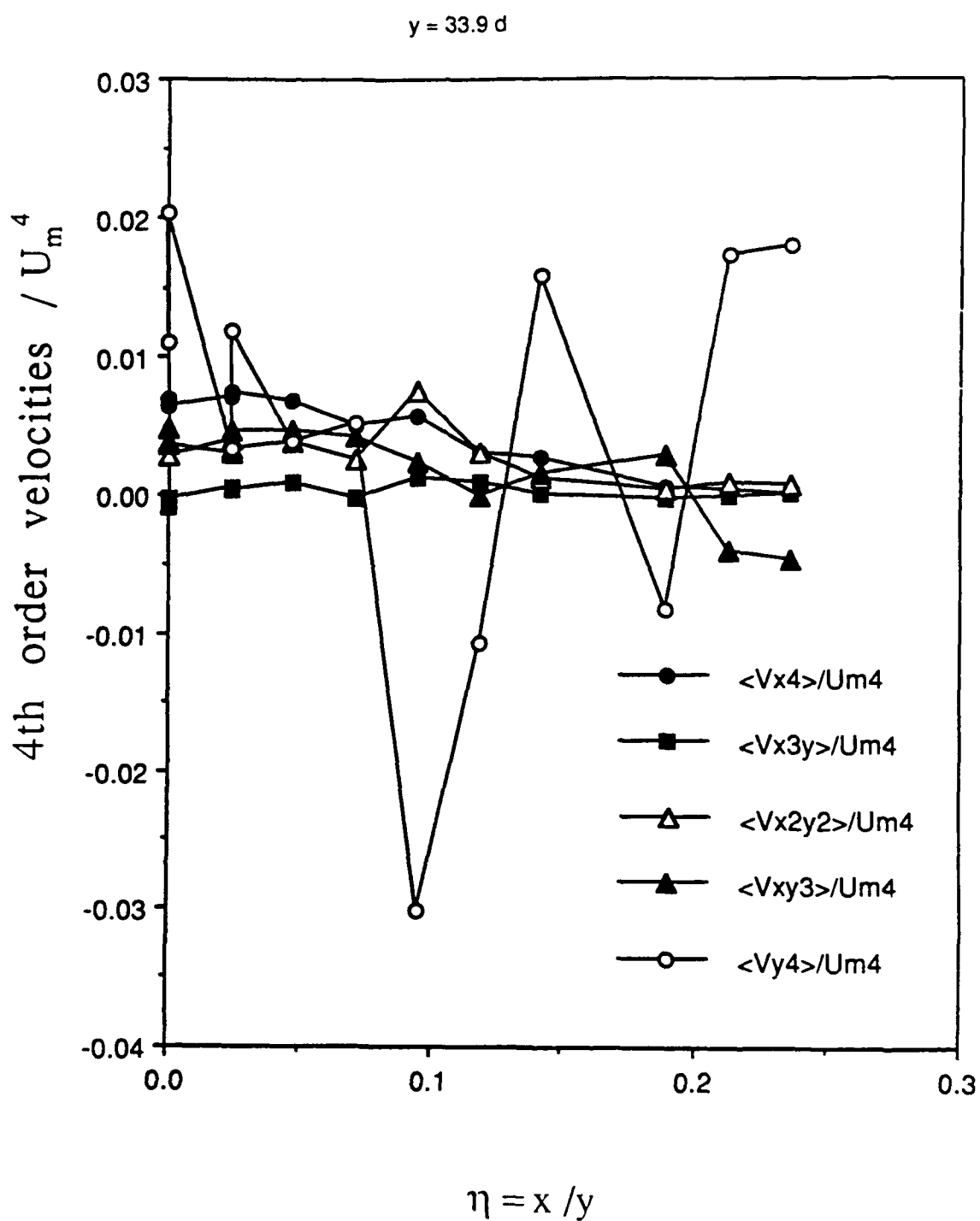


FIG. 36. Quadruple velocity correlations across the jet

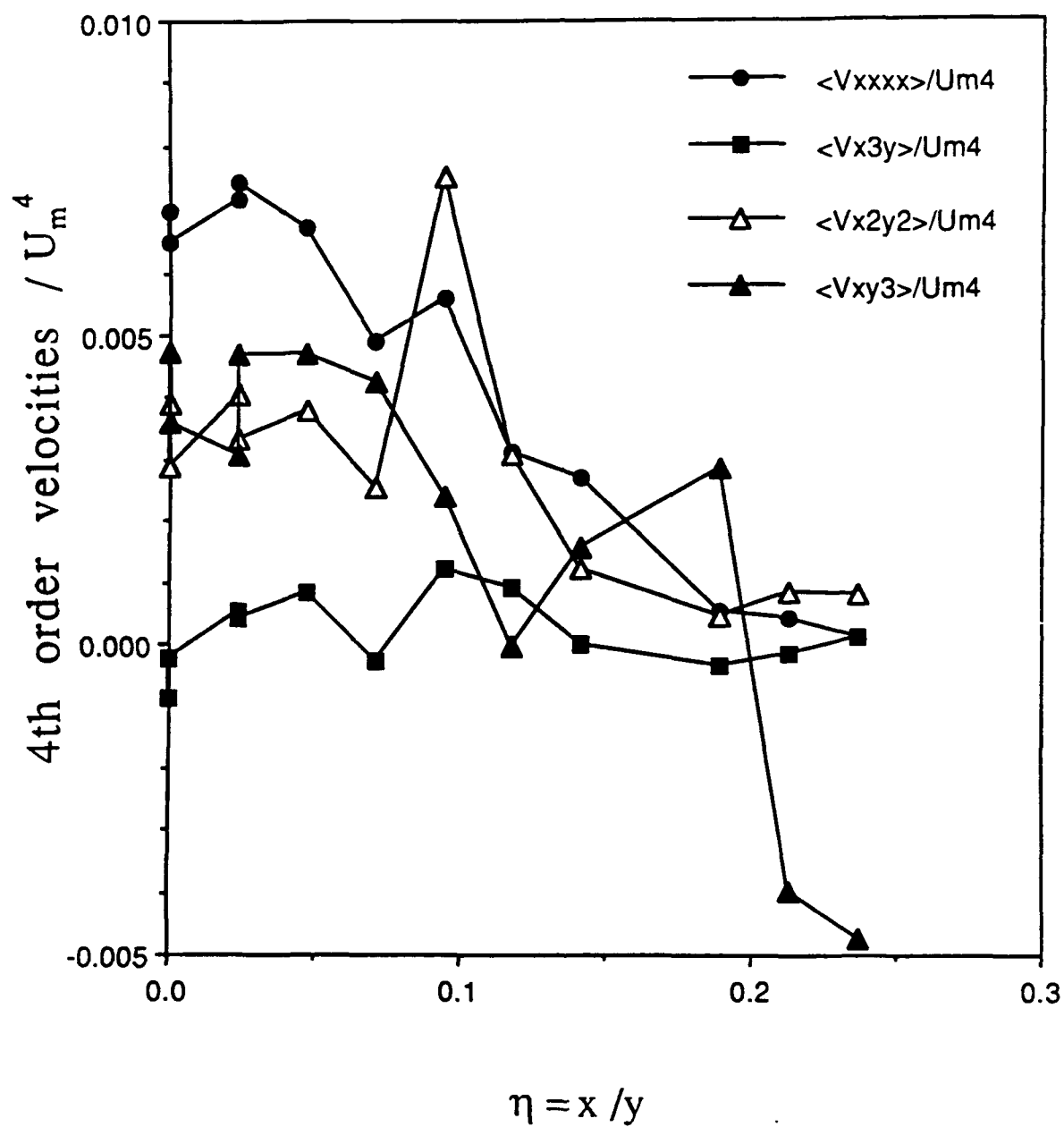
$y = 33.9 d$ 

FIG. 37. Quadruple velocity correlations across the jet, neglecting the $\langle V_{y4} \rangle$ term

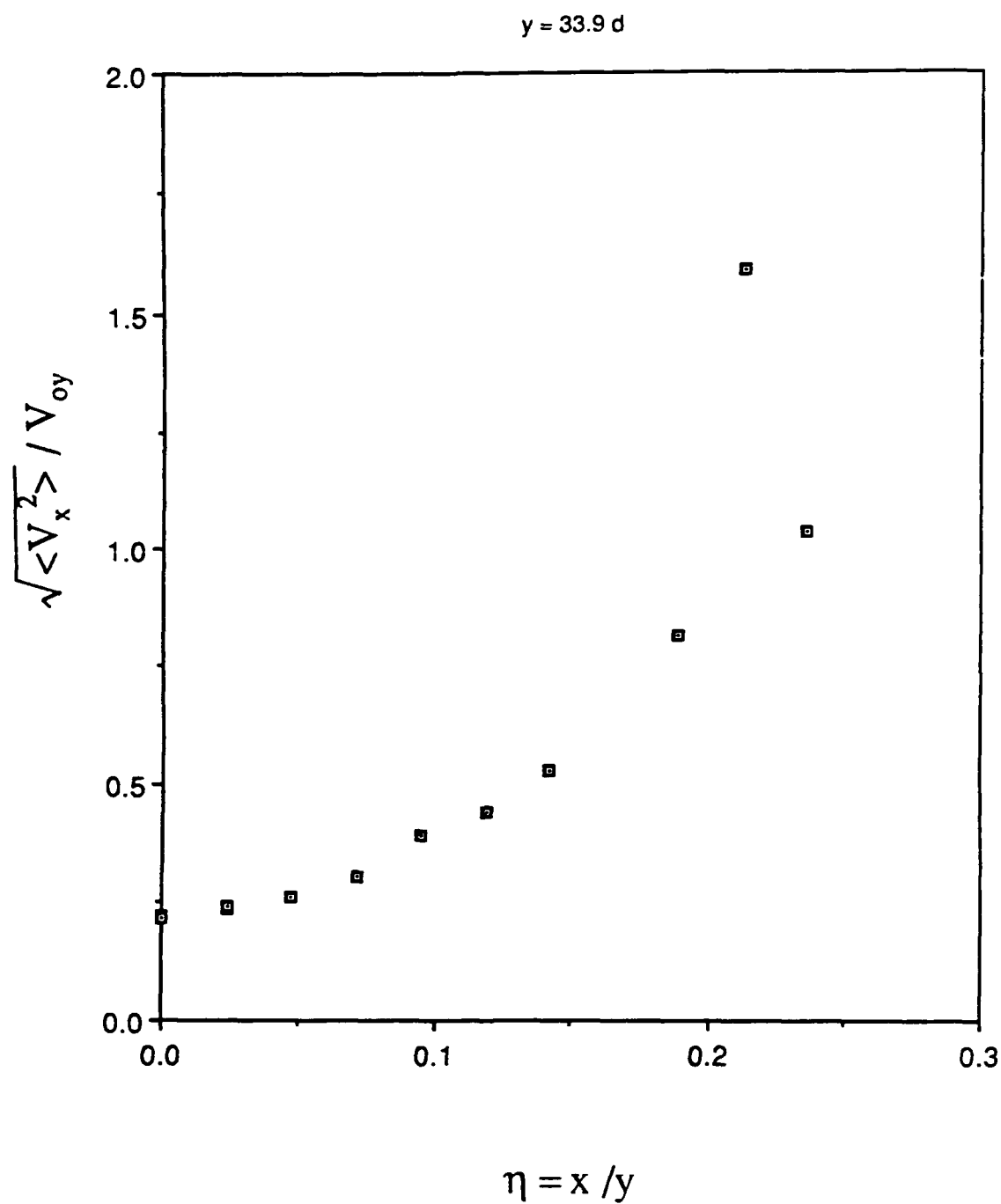


FIG. 38. Distribution of the Radial turbulent intensity across the jet

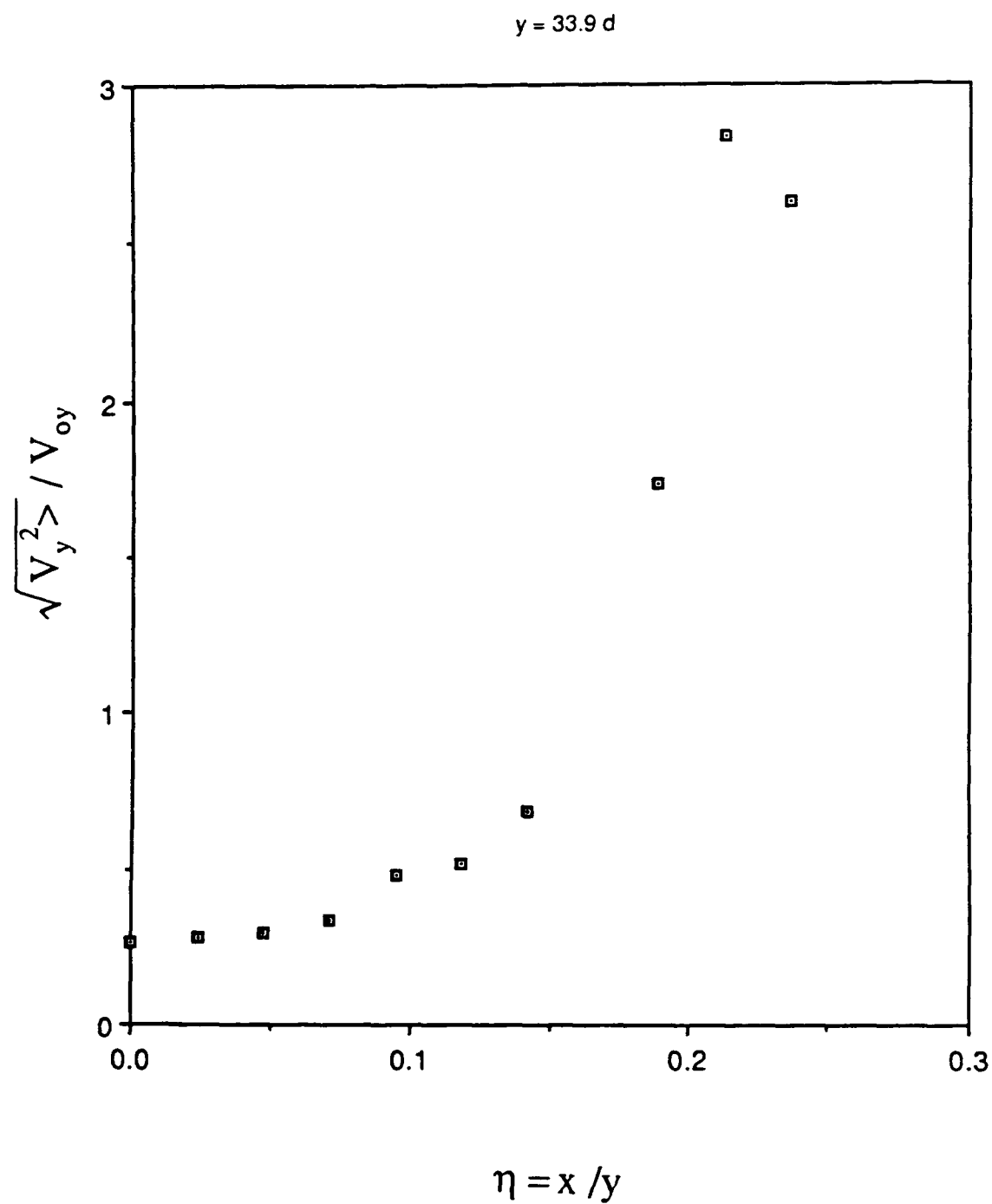


FIG. 39. Distribution of the axial turbulent intensity across the jet

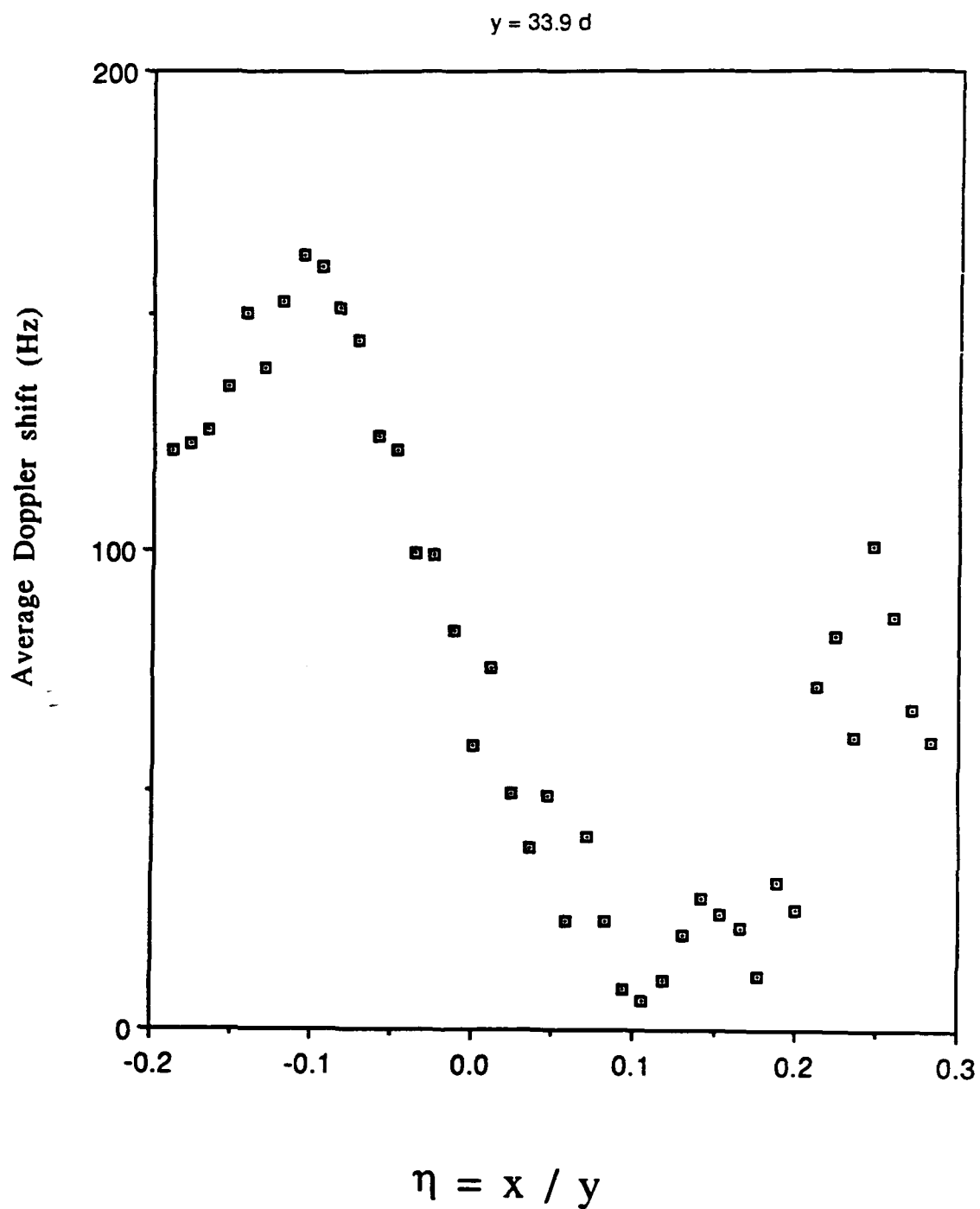


FIG. 40. Doppler shifts from forward scattering across the jet

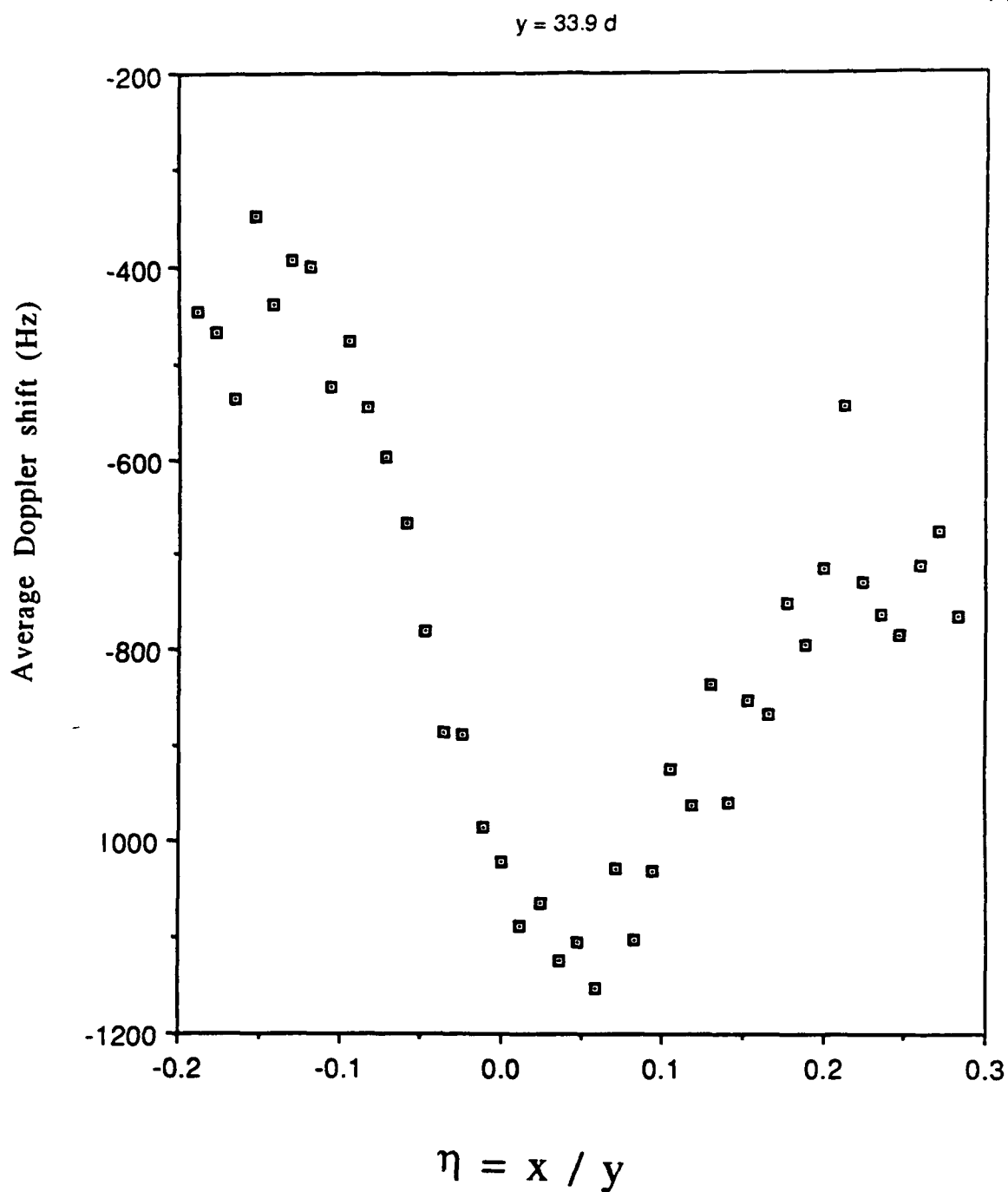


FIG. 41. Doppler shifts from back scattering across the jet

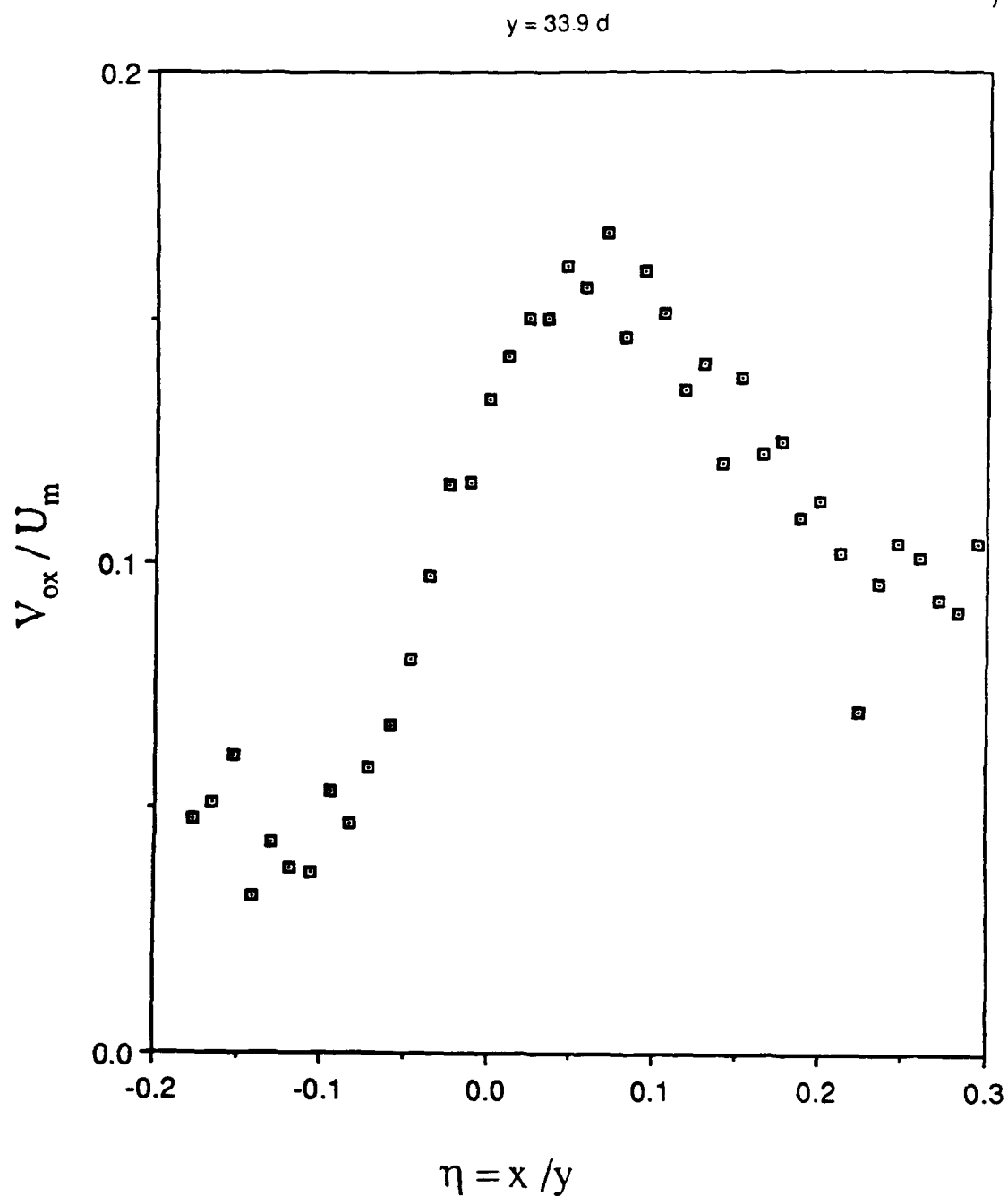


FIG. 42. Radial mean velocity across the jet from Translational scanning measurements

DISCUSSION OF POSSIBLE ERRORS

We are able to map out the turbulent velocities for a submerged water jet with the nonlinear scattering apparatus. This statement is founded upon the agreement between the results obtained by our analysis, general comparisons with the measurements obtained by Wygnanski, and by comparisons with the pitot tube results. The disagreement in the detailed nature of the profiles of the higher order correlations is attributed to the differences in the turbulent jets. Wygnanski uses a bare nozzle in a large room. Our jet nozzle is baffled by a 6 inch diameter flat plate and ejects into a cubic meter tank of water. The boundaries of the sides of the tank and opposite wall, in addition to the entrained flow having to go around the baffled orifice, are suspected to have interfered with a more simple entrainment of fluid into the jet. These differences are known to have small effects upon the structure of the mean flow profiles. The second order correlations were not expected to compare well with Wygnanski's jet - although they did. At the higher orders, the correlations do generally compare well, but not in detail. It is believed that this scattering experiment can predict mean flows to $\approx 1.5\%$, second order correlations to $\approx 5\%$, third order correlations to $\approx 10\%$, and fourth order correlations to $\approx 25\%$, if the turbulence is not too weak.

There are some large errors in the tails of our curves ($\eta > 0.15$) that were caused when radio frequency interference from the Severn Naval Station's radio transmissions was detected in the sum frequency spectra. The interference forced us to delete some of the spectra that were obtained in the set of 80 scattering angles per scan position. This in turn reduced the number of data points that were used to fit the curves. Therefore, our curve fitting routines on the skirts of the jet (having fewer data points) resulted in larger errors in the predictions of the turbulent velocity correlations.

It is noticed that near the edges of the jet, errors are generally larger for the axial velocity measurements than the

radial ones. This may be explained in terms of the optimum scanning angles. At the optimum angles, correlations between the spectral moments and the turbulent velocities leads to a least error. Angular scattering for θ_* between 60° and 120° , or between 240° and 300° are not possible as the transducer units are translated off axis. Here, the transducer units are physically moved into the turbulent jet. Unfortunately, the maximum values of K_y occur in this range. Doppler shift contributions from the factor $K_y V_y$ need to be large if the velocity component V_y to be measured is very small. Therefore, reducing the scans in this range degrades the ability of the apparatus to determine the axial flow. The angles from $\theta_* = -30^\circ$ to 30° , and from 150° to 210° are the extreme forward and back scattered angles. In translating the interaction region across the jet at these angles, the transducer units do not interfere with the turbulent jet. Therefore, a full range of values for K_x is covered at each radial position producing Doppler shift contributions from the factor $K_x V_x$ that are significant. Moreover, this extreme forward or back scattering range corresponds to a maximum for K_x . Therefore, Doppler shift predictions from the factor $K_x V_x$ lead to very small errors in predicting V_x .

CONCLUSIONS

Nonlinear crossed beam scattering in the presence of turbulence produces a sum frequency component that radiates outside the interaction region. Measurements of the Doppler shift, spectral broadening, skewness, and kurtosis (of the scattered intensity spectrum) can be used to predict mean flow velocities as well as second, third, and fourth order turbulent velocity correlation coefficients. The performance of the crossed beam experiment in measuring turbulent flow is very sensitive to the ratio $\gamma = k_{0-} / k_{0+}$. If $\gamma \ll 1$, then scattered measurements in the forward ($\theta_s = 0^\circ$) or back ($\theta_s = 180^\circ$) scattered directions will be highly correlated with the component of velocity along the direction of the bisecting line between the sending transducer axes and the point of overlap.

This nonlinear scattering phenomenon is highly sensitive to even the smallest vorticity disturbances that were created in the water tank. This diagnostic tool is a viable alternative to conventional turbulent flow measuring devices that use hot film probes or laser Doppler techniques.

ACKNOWLEDGEMENTS

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APPENDIX A: DOPPLER THEORY

A. Single beam scattering of sound by turbulence

The scattering of sound by turbulence predicts, in theory, that the scattered sound waves will be Doppler shifted by an amount equal to $\vec{K} \cdot \vec{V}$, where $\vec{K} = \vec{k}_s - \vec{k}_i$ is the wavevector of the scattered wave, \vec{k}_s , minus the wavevector of the incident wave, \vec{k}_i . Define the velocity vector of a fluid particle to be \vec{V} . One can derive the Doppler shift expression by studying the relative phase of an incident acoustic wavefront that has been scattered by a moving fluid particle or turbulent eddy. Figure 43 illustrates how a turbulent eddy can scatter sound.

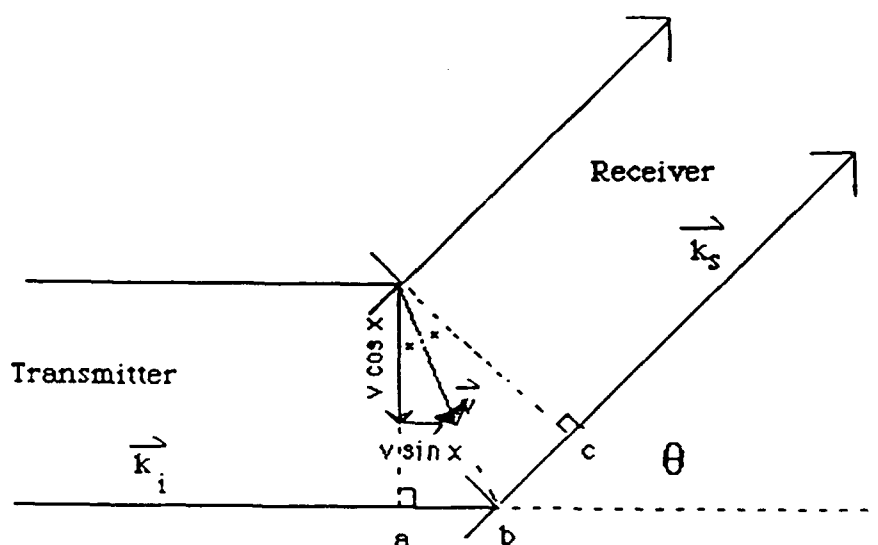


FIG. 43. Scattering of an incident sound wave by a turbulent eddy

If the wavefront is deflected through an angle θ by the action of the moving fluid particle, there is a change in direction of the wavefront. The change in the wave's path causes one portion of the wave front to travel a longer distance

$(\overline{ab} + \overline{bc})$ than the other. After the scattering, the waves propagate along the new path. However, because of this path difference, the scattered wave will exhibit a phase shift (with respect to the incident wave) that is given by:

$$\Delta\phi = k_i \overline{ab} + k_s \overline{bc}.$$

For turbulent fluid particles, the particle velocity \vec{V} , is always changing in time. This causes the relative paths \overline{ab} and \overline{bc} to vary with time. These path variations change the phase shift, $\Delta\phi$ with respect to time. One can relate the time dependent phase shifts in the scattered wave to the Doppler shifts, ω_d , using the expression below.

$$\frac{\Delta\phi}{\Delta t} = \omega_d = -k_i v \sin x - k_s v \sin x. \quad (A1)$$

Here, $\frac{\Delta\phi}{\Delta t}$ is the time rate of change in phase. The negative signs appear in this expression because the particle velocity components move away from the source and away from the receiver, respectively. This results in a net down Doppler shift. If $k_i = k_s$ then ω_d becomes

$$\omega_d = -2k_s v \sin (\theta/2), \text{ where } \theta = 2x. \quad (A2)$$

Now we replace v in the above model with \vec{V} , the vector turbulent particle velocity. The magnitude of \overline{ab} is described by

$$\overline{ab} = k_i V \cos \alpha = \vec{k}_i \cdot \vec{V}. \quad (A3)$$

The value is negative because the direction of \vec{V} along \vec{k}_i points away from the transducer. Similarly,

$$\overline{bc} = k_s V \cos \alpha = \vec{k}_s \cdot \vec{V}. \quad (A4)$$

This value is positive since \vec{bc} is towards the receiver. The net result is

$$\begin{aligned}\frac{\Delta\phi}{\Delta t} = \omega_d &= -(\vec{k}_i \cdot \vec{V}) + (\vec{k}_s \cdot \vec{V}) \\ &= (\vec{k}_s - \vec{k}_i) \cdot \vec{V} \\ &= \vec{K} \cdot \vec{V}.\end{aligned}\tag{A5}$$

B. Nonlinear crossed beam scattering of sound by turbulence

It is known from Korman and Beyer's nonlinear scattering theory⁵ that the nonlinearly scattered sum frequency component also undergoes a Doppler shift. Using this model, one can relate \vec{k}_s and \vec{k}_i to nonlinear crossed beam parameters. Let the nonlinearly scattered sum frequency wavevector \vec{k}_s be equal to

$$\vec{k}_s = k_{0+} \vec{n} = (k_{01} + k_{02}) \vec{n}, \tag{A6}$$

where \vec{n} is a unit vector that points from the interaction region to the receiver. Define the incident wavevector, \vec{k}_i as the linear combination of the incident wavevectors from each primary wave. Then, \vec{k}_i becomes

$$\vec{k}_i = k_{01} \vec{n}_{01} + k_{02} \vec{n}_{02}, \tag{A7}$$

which are the two emitted waves from the transmitting transducers #1 and #2. The difference between the scattered and incident wave vectors, $\Delta\vec{k}$, can be expressed by

$$\begin{aligned}\vec{k}_s - \vec{k}_i &= [k_{01} \vec{n} - k_{01} \vec{n}_{01}] + [k_{02} \vec{n} - k_{02} \vec{n}_{02}], \\ &= \vec{K}_1 + \vec{K}_2 \\ &= \vec{K}_+.\end{aligned}\tag{A8}$$

Here, one has defined \vec{K}_1 and \vec{K}_2 as individual scattering vectors of the nonlinear scattering experiment. Further, define $\vec{K}_+ = \vec{K}_1 + \vec{K}_2$ to be the resultant scattered wave number for the nonlinear scattering theory. Thus we have our relation for the Doppler shift, $\omega_d = \vec{K}_+ \cdot \vec{V}$ which is based upon the scattering of longitudinal sound waves from transverse (or rotational) fluid particle flow.

C. Doppler quantum theory

The nonlinear scattering phenomena involves four principle parts: two incident focused sound waves, a scattered wave, and a turbulent eddy that scatters the incident wave. To examine the scattering effects in the interaction region, first study a model for conventional single beam scattering. Later, one can expand the model to include both incident beams and study the nonlinear scattering from crossed beams.

1. Conventional single beam scattering theory

In conventional single beam scattering, an incident sound wave is scattered by the action of a turbulent eddy. The resulting momentum change is shown in Figure 44.

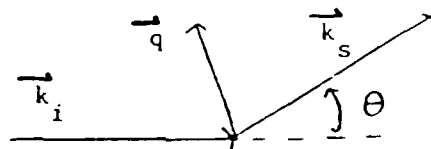


FIG. 44. Momentum change of incident beam due to scattering

To find a relationship between the incident and scattered waves, use the principles of momentum and energy conservation. The momentum and energy of an excitation (or

wave packet) may be expressed by $\hbar\vec{k}$, $\hbar\omega$, respectively, where \hbar is Planck's constant divided by 2π , \vec{k} is a wave vector of a phonon excitation, and ω is the angular frequency of the wave excitation. Thus, the momenta of the incident and scattered phonons become $\hbar\vec{k}_i$ and $\hbar\vec{k}_s$, respectively. The energies of the phonon excitations are $\hbar\omega_i$ and $\hbar\omega_s$. For the scattering model, let \vec{q} denote the wave vector excitation of the turbulent eddy and ω_t the corresponding angular frequency of the turbulent eddy excitation. Thus, its momenta and energy are $\hbar\vec{q}$ and $\hbar\omega_t$.

The conservation principles are

$$\vec{k}_i + \vec{q} = \vec{k}_s \quad \text{conservation of momentum (A9)}$$

$$\omega_i + \omega_t = \omega_s \quad \text{conservation of energy . (A10)}$$

From momentum and energy conservation, one can solve for the scattered wave number \vec{q} and the turbulent excitation frequency:

$$\vec{q} = (\vec{k}_s - \vec{k}_i) \quad (\text{A11})$$

$$\omega_t = (\omega_s - \omega_i) . \quad (\text{A12})$$

Define \vec{q} to be \vec{K} , the scattered wave vector, and ω_t to be ω_d , the Doppler shift. Thus the excitation frequency of the turbulent eddy is equal to the Doppler shift in the incident wave. For sound waves, the wave number is directly related to its excitation frequency.

$$\omega_i = k_i c \quad (\text{A13})$$

$$\omega_s = k_s c , \quad (\text{A14})$$

where c is the speed of sound in water. For a turbulent eddy, the excitation frequency is known to be

$$\omega_t = \vec{q} \cdot \vec{V} , \quad (\text{A15})$$

where \vec{V} is the velocity of the turbulent eddy.

Make the following convenient substitutions:

$$\vec{k}_i = k_i \mathbf{n}_i, \quad (\text{A16})$$

where k_i is the wave number and \mathbf{n}_i is a unit vector in the direction of propagation of the incident wave. Similar substitutions are used for the scattered wave:

$$\vec{k}_s = k_s \mathbf{n}_s. \quad (\text{A17})$$

From the equation of momentum conservation

$$\vec{q} = (k_s \mathbf{n}_s - k_i \mathbf{n}_i), \quad (\text{A18})$$

the turbulent excitation frequency is now given by

$$\begin{aligned} \omega_t &= \vec{q} \cdot \vec{V} \\ &= (k_s \mathbf{n}_s - k_i \mathbf{n}_i) \cdot \vec{V}. \end{aligned} \quad (\text{A19})$$

The Doppler shift is the excitation frequency ω_t or $\omega_s - \omega_i$. It can be expressed by

$$\omega_s - \omega_i = (\omega_s \mathbf{n}_s - \omega_i \mathbf{n}_i) \cdot \vec{V}/c. \quad (\text{A20})$$

The Doppler shift is now cast in a form that can be used to interpret the experimental geometry. Now, one can solve for ω_s :

$$\omega_s = \omega_i [1 - \mathbf{n}_i \cdot (\vec{V}/c)] / [1 - \mathbf{n}_s \cdot (\vec{V}/c)]. \quad (\text{A21})$$

In the experiments of interest, the magnitude of the flow velocity $|\vec{V}|$ is much less than the speed of sound, c . Since $|\vec{V}|/c \ll 1$,

$$\omega_s \approx \omega_i [1 - \mathbf{n}_i \cdot (\vec{V}/c)] [1 + \mathbf{n}_s \cdot (\vec{V}/c)]. \quad (\text{A22})$$

If one drops the second order term in A22, the relation between the scattered wave's angular frequency and the incident wave's angular frequency becomes

$$\omega_s \approx \omega_i [1 + (\mathbf{n}_s - \mathbf{n}_i) \cdot (\vec{V}/c)] . \quad (\text{A23})$$

These relations predict that the scattered waves will gain/lose energy {depending upon the sign of $(\mathbf{n}_s - \mathbf{n}_i) \cdot (\vec{V}/c)$ } from the excitations which have been modeled as fluctuations of the turbulent eddies.

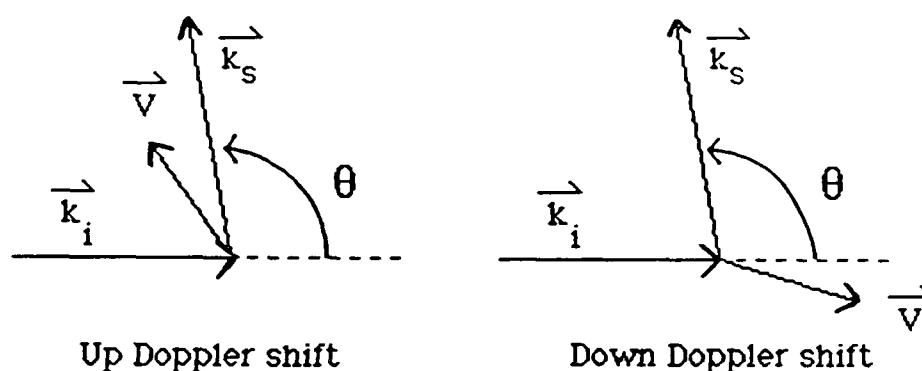


FIG. 45. Scattering geometries that produce up Doppler or down Doppler shifts

In Figure 45, the scattering diagram on the left describes a scattering geometry in which the $(\mathbf{n}_s - \mathbf{n}_i) \cdot (\vec{V}/c)$ term is positive, representing an up Doppler shift. Conversely, the diagram on the right shows a scattering geometry in which the $(\mathbf{n}_s - \mathbf{n}_i) \cdot (\vec{V}/c)$ term is negative, corresponding to a down Doppler shift.

2. Nonlinear crossed beam theory

In nonlinear crossed beam scattering, two incident sound beams cross in the presence of a turbulent eddy. The interaction creates a scattered sum frequency component whose frequency is the algebraic sum of the frequencies of the incident beams. The resulting momentum change for this interaction is shown in Figure 46.

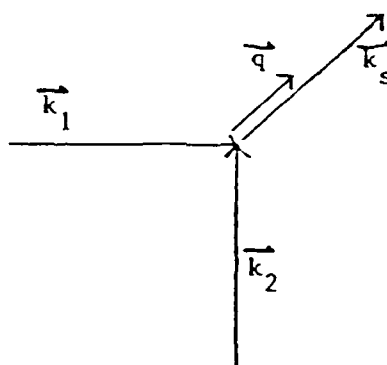


FIG. 46. Momentum changes of incident beams due to nonlinear scattering

In the nonlinear interaction, there are two distinct incident waves, each with its own momentum and energy. As a result, the conservation equations become

$$\vec{k}_1 + \vec{k}_2 + \vec{q} = \vec{k}_s, \quad (\text{A24})$$

$$\omega_1 + \omega_2 + \omega_i = \omega_s. \quad (\text{A25})$$

One can solve equations A24 and A25 to find a relationship between \vec{q} and ω_i :

$$\vec{q} = \vec{k}_s - (\vec{k}_1 + \vec{k}_2) \quad (\text{A26})$$

$$\omega_t = \omega_s - (\omega_1 + \omega_2) . \quad (A27)$$

These relations become more useful by making the following definitions:

$$\begin{aligned} \omega_+ &= \omega_1 + \omega_2 \\ \vec{k}_1 &= k_{01} \vec{n}_{01} \\ \vec{k}_2 &= k_{02} \vec{n}_{02} \\ \vec{k}_s &= (k_{01} + k_{02})\vec{n} . \end{aligned} \quad (A28)$$

Here, define two wave numbers

$$\begin{aligned} k_{01} &= \omega_{01} / c , \\ k_{02} &= \omega_{02} / c , \end{aligned}$$

and their corresponding incident unit vector directions to be \vec{n}_{01} and \vec{n}_{02} , respectively. Let \vec{n} be a unit vector in the direction of the scattered wave. From these definitions \vec{q} and ω_t become

$$\vec{q} = (k_{01} + k_{02})\vec{n} - (k_{01} \vec{n}_{01} + k_{02} \vec{n}_{02}) \quad (A29)$$

$$\omega_t = \omega_s - \omega_+ , \quad (A30)$$

which can be cast in the form

$$\vec{q} = \vec{K}_+ \quad (A31)$$

$$\omega = \omega_s - \omega_+ \quad (A32)$$

by using the following definitions

$$\begin{aligned} \vec{K}_1 &= k_{01} (\vec{n} - \vec{n}_{01}) \\ \vec{K}_2 &= k_{02} (\vec{n} - \vec{n}_{02}) \\ \vec{K}_+ &= \vec{K}_1 + \vec{K}_2 . \end{aligned} \quad (A33)$$

Thus, the resulting Doppler shifts act as if the superposition of two simultaneous conventional single beam scatterings had occurred.

From the conservation equations for nonlinear scattering, one can prove that two collinear beams can produce a radiated sum frequency component whereas two crossed beams cannot unless turbulence is present in the interaction.

In the absence of turbulence, \bar{q} and ω_i become zero, leaving the two incident beams to add vectorially. In Fig. 47, the diagram at the left shows the momentum of the collinear beams adding vectorially to the sum frequency vector. The same Fig. 47 also shows the vector addition of the momentum of two crossed beams. Notice that the crossed beams will not add to the sum frequency vector without the additional momentum supplied by the turbulent eddy.

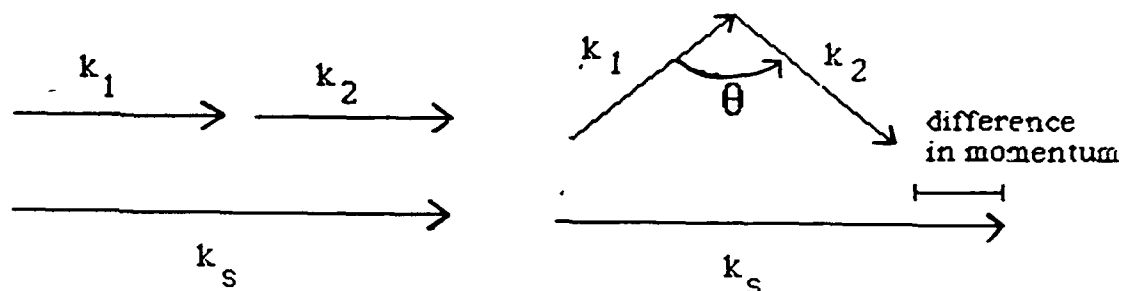


FIG. 47. Momentum diagrams for collinear and crossed beams

In the collinear case, it is possible to add the incident wave vectors and have the result $k_s = (k_{01} + k_{02})$ which is the wave number of the scattered wave. If the two beams cross at an angle θ , the magnitudes of the incident beams add to

$$|\vec{k}_1 + \vec{k}_2| = \sqrt{k_{01}^2 + k_{02}^2 - 2k_{01}k_{02} \cos \theta} \quad (\text{A34})$$

which is less than $(k_{01} + k_{02})$. This is true for any angle other than 180° . Thus, the momentum of the crossed incident beams alone is insufficient to create the sum frequency component. The additional momentum needed to radiate the sum frequency component comes from turbulent momenta excitation.

APPENDIX B: FOURIER COEFFICIENTS

The finite Fourier series for the K_x and K_y terms are presented on the next pages in tabular format. Each group of coefficients is calculated by the method outlined in the spectral theory (eqs. 21 to 24).

The following definitions are used throughout these tables:

$$\begin{aligned} K_x(\theta) &= k_{0+} F(\theta) \quad \text{where} \quad F(\theta) = 1 - \frac{\sqrt{2}}{2} \cos \theta - \gamma \sin \theta, \\ K_y(\theta) &= k_{0+} G(\theta) \quad \text{where} \quad G(\theta) = -\frac{\sqrt{2}}{2} \sin \theta - \gamma \frac{\sqrt{2}}{2} \cos \theta, \\ \text{and } \gamma &= k_{0-} / k_{0+}. \end{aligned} \quad (B1)$$

The coefficients are used in the following equations of average frequency, variance, third moment, and fourth moment to determine the turbulent flow velocities.

Average frequency

$$\begin{aligned} \langle \omega_d \rangle - \omega_{0+} &= -K_x V_{ox} - K_y V_{oy} \\ &= -k_{0+} F(\theta) V_{ox} - k_{0+} G(\theta) V_{oy} \end{aligned} \quad (B2)$$

Second Moment

$$\begin{aligned} \sigma^2 = \langle (\omega_d - \langle \omega_d \rangle)^2 \rangle &= k_{0+}^2 [F^2(\theta) \langle V_x^2 \rangle + G^2(\theta) \langle V_y^2 \rangle + \\ &2F(\theta)G(\theta) \langle V_x V_y \rangle] \end{aligned} \quad (B3)$$

Third Moment

$$\begin{aligned} \langle (\omega_d - \langle \omega_d \rangle)^3 \rangle &= -k_{0+}^3 [F^3(\theta) \langle V_x^3 \rangle + 3F^2(\theta)G(\theta) \langle V_x^2 V_y \rangle + \\ &3F(\theta)G^2(\theta) \langle V_x V_y^2 \rangle + G^3(\theta) \langle V_y^3 \rangle] \end{aligned} \quad (B4)$$

Fourth Moment

$$\begin{aligned} \langle (\omega_d - \langle \omega_d \rangle)^4 \rangle &= -k_{0+}^4 [F^4(\theta) \langle V_x^4 \rangle + 4F^3(\theta)G(\theta) \langle V_x^3 V_y \rangle + \\ &6F^2(\theta)G^2(\theta) \langle V_x^2 V_y^2 \rangle + 4F(\theta)G^3(\theta) \langle V_x V_y^3 \rangle + \\ &G^4(\theta) \langle V_y^4 \rangle] \end{aligned} \quad (B5)$$

In the following Tables (I - IV) the short hand notation $GG = G^2(\theta)$, $FG = F(\theta)G(\theta)$, etc. is used.

	a_0	$\cos \theta$	$\cos 2\theta$	$\cos 3\theta$	$\cos 4\theta$
Cosine coefficients for the average frequency					
F	1	$-\sqrt{2}/2$	0	0	0
G	0	$-\sqrt{2}/2$	0	0	0

TABLE I. Part 1 of Fourier coefficients for the
average frequency

	$\sin \theta$	$\sin 2\theta$	$\sin 3\theta$	$\sin 4\theta$
Sine coefficients for the average frequency				
F	$-\gamma$	0	0	0
G	$-\sqrt{2}/2$	0	0	0

TABLE I. Part 2 of Fourier coefficients for the average frequency

TABLE II. Part I of Fourier coefficients for the variance

	sin θ	sin 2θ	sin 3θ	sin 4θ
Sine coefficients for the variance				
FF	-2γ	$\frac{\gamma\sqrt{2}}{2}$	0	0
FG	$-\frac{\sqrt{2}}{2}$	$\frac{1}{4} + \frac{\gamma^2\sqrt{2}}{2}$	0	0
GG	0	$\frac{\gamma}{2}$	0	0

TABLE II. Part 2 of Fourier coefficients
for the variance

	a_0	$\cos \theta$	$\cos 2\theta$	$\cos 3\theta$	$\cos 4\theta$
Cosine coefficients for the third moment					
FFF	$\frac{1}{4} + \frac{3x^2}{2}$	$-\frac{7\sqrt{2}}{4}$	$\frac{3}{4} - \frac{3x^2}{2}$	$\frac{3x^2\sqrt{2}}{4} - \frac{\sqrt{2}}{8}$	0
FFG	$\frac{x\sqrt{2}}{2} + \frac{x}{2}$	$-\frac{3x\sqrt{2}}{4}$	$x - \frac{x\sqrt{2}}{2}$	$\frac{x}{2} - \frac{x\sqrt{2}}{8} + \frac{x^3\sqrt{2}}{4}$	0
FGG	$\frac{1}{4} + \frac{x^2}{4}$	$-\frac{x^2\sqrt{2}}{4}$	$\frac{x^2-1}{4}$	$\frac{\sqrt{2}}{8} + \frac{x^2}{2} - \frac{x^2\sqrt{2}}{8}$	0
GGG	0	$-\frac{x^3\sqrt{2}}{4}$	0	$\frac{3x\sqrt{2}}{8} - \frac{x^3\sqrt{2}}{8}$	0

TABLE III. Part 1 of Fourier coefficients for the third moment

	$\sin \theta$	$\sin 2\theta$	$\sin 3\theta$	$\sin 4\theta$
Sine coefficients for the third moment				
FFF	$-4\gamma - \frac{\gamma^2}{2}$	$\frac{3\sqrt{2}}{2} \gamma$	$\frac{\gamma^3}{2} - \frac{\gamma^2}{4}$	0
FFG	$-\frac{3\sqrt{2}}{4} - \gamma^2$	$\frac{1}{2} + \frac{\gamma^2 \sqrt{2}}{2}$	$-\frac{\sqrt{2}}{8} + \frac{\gamma^2 \sqrt{2}}{4} - \frac{\gamma^2}{2}$	0
FGG	$-\frac{\gamma \sqrt{2}}{2} + \frac{\gamma^3}{2}$	$\frac{\gamma}{2}$	$\frac{\gamma}{4} - \frac{\gamma \sqrt{2}}{4} - \frac{\gamma^3}{4}$	0
GGG	$-\frac{3\gamma^2 \sqrt{2}}{4}$	0	$\frac{\sqrt{2}}{8} - \frac{3\gamma^2 \sqrt{2}}{8}$	0

TABLE III. Part 2 of Fourier coefficients for
the third moment

	a0	cos θ	cos 2θ	cos 3θ	cos 4θ
Cosine coefficients for the fourth moment					
FFFF	$\frac{8^3}{32} + \frac{2^7}{8} \delta + \frac{3}{8} \delta^4$	$-3\sqrt{2}$	$\frac{13}{8} - 3\delta^2 - \delta^4$	$-\frac{\sqrt{2}}{2} + 3\sqrt{2} \delta^2$	$\frac{1}{32} - \frac{3\delta^2}{8} + \frac{\delta^4}{8}$
FFFG	$\frac{27}{32} \delta [1 + \sqrt{2}] + \frac{3\delta^3}{16} [1 + \sqrt{2}]$	$-\frac{5\sqrt{2}}{4} \delta$	$\frac{7}{8} \delta - \frac{3\delta\sqrt{2}}{4} - \frac{\delta^3\sqrt{2}}{4}$	$\frac{3}{2} \delta - \frac{3\delta\sqrt{2}}{8} + \frac{3\delta^3\sqrt{2}}{4}$	$\frac{\delta}{32} - \frac{3\delta\sqrt{2}}{32} - \frac{3\delta^3}{16} + \frac{\delta^3\sqrt{2}}{16}$
FFGG	$\frac{9}{32} + \frac{17\delta^2}{32} + \frac{\delta^2\sqrt{2}}{8} + \frac{\delta^4}{16}$	$-\frac{\delta\sqrt{2}}{2}$	$\frac{\delta^2}{8} - \frac{1}{4}$	$\frac{\sqrt{2}}{4} - \frac{\delta^2\sqrt{2}}{4}$	$-\frac{1}{32} + \frac{3\delta^2}{32} - \frac{\delta^2\sqrt{2}}{8} - \frac{\delta^4}{16}$
FGGG	$\frac{3}{32} \delta + \frac{3\delta\sqrt{2}}{32} + \frac{3\delta^3}{32} + \frac{\delta^3\sqrt{2}}{8}$	$-\frac{\delta^3\sqrt{2}}{4}$	$-\frac{\delta\sqrt{2}}{8} + \frac{\delta^3}{8}$	$\frac{\delta\sqrt{2}}{2} - \frac{\delta^3\sqrt{2}}{8}$	$-\frac{3\delta}{32} + \frac{\delta\sqrt{2}}{8} + \frac{\delta^3}{32} - \frac{\delta^3\sqrt{2}}{8}$
GGGG	$\frac{3}{32} + \frac{3\delta^2}{16} + \frac{3\delta^4}{32}$	0	$-\frac{1}{8} + \frac{\delta^2}{8}$	0	$\frac{1}{32} - \frac{3\delta^2}{16} + \frac{\delta^4}{32}$

TABLE IV. Part 1 of Fourier coefficients for
the fourth moment

	$\sin \theta$	$\sin 2\theta$	$\sin 3\theta$	$\sin 4\theta$
Sine coefficients for the fourth moment				
FFFF	-10χ	$\frac{13}{4}\chi\sqrt{2} + \frac{\chi^3\sqrt{2}}{2}$	$-3\chi + 2\chi^3$	$\frac{\chi\sqrt{2}}{8} - \frac{\chi^3\sqrt{2}}{4}$
FFFG	$-\frac{5\sqrt{2}}{4} - 3\chi^2$	$\frac{13}{16} + \frac{3\chi^2}{8} + \frac{13\sqrt{2}}{16}\chi^2 + \sqrt{2}\chi^4/8$	$-\frac{3\sqrt{2}}{8} + \frac{3\chi^2\sqrt{2}}{4} - \frac{3\chi^2}{2}$	$\frac{1}{32} - \frac{5\chi^2}{16} + \frac{3\chi^2\sqrt{2}}{32} - \chi^4\sqrt{2}/16$
FFGG	$-\chi\sqrt{2} - \chi^3$	$\frac{5\chi}{8} + \frac{\chi\sqrt{2}}{8} + \frac{\chi^3}{4} + \frac{\chi^3\sqrt{2}}{8}$	$\frac{\chi}{2} - \frac{\chi\sqrt{2}}{2} - \frac{\chi^3}{2}$	$\frac{\chi}{16} - \frac{\chi\sqrt{2}}{16} - \frac{\chi^3}{16} + \frac{\chi^3\sqrt{2}}{16}$
FGGG	$-\chi^2\sqrt{2}$	$\frac{1}{16} + \frac{3\chi^2}{16} + \frac{3\chi^2\sqrt{2}}{16} + \chi^4\sqrt{2}/16$	$\frac{\sqrt{2}}{8} - \frac{\chi^2\sqrt{2}}{2}$	$-\frac{1}{32} + \frac{3\chi^2}{32} - \frac{3\chi^2\sqrt{2}}{52} + \frac{\chi^4\sqrt{2}}{32}$
GGGG	0	$\frac{\chi}{4} + \frac{\chi^3}{4}$	0	$-\frac{1}{8} + \frac{\chi^3}{8}$

TABLE IV. Part 2 of Fourier coefficients for the fourth moment

APPENDIX C: COMPUTER PROGRAMS

1. Correlator - Macintosh program to compile a list of velocity correlations
2. Mean velocity correlations - Macintosh program that uses the least squares method to find the axial and mean velocities.
3. Rotator - Apple IIe program that automates the rotational experiment.
4. Analyzer - Apple IIe program to calculate spectral moments.
5. Mac - Pascal program used to calculate spectral moments.

CORRELATOR PROGRAM

```
'This program compiles the velocity information
'from one rotational data run into a single text file.
'Also computes the rms, skewness, and kurtosis
'values of the turbulent parameters
'
```

```
DEFDBL a-z
```

```
DIM variance(3), mean(2), cubic(4), kurt(5) 'input functions
```

```
DIM rms(3), rmsMean(4), S(4), K(5) 'output functions
```

```
GOSUB inputTitle
```

```
PRINT "Will you want to output to disk (y/n)? ";
```

```
INPUT "";ans$
```

```
IF NOT LEFT$(ans$,1) = "n" THEN GOSUB outfile ELSE nofile = 1
```

```
GOSUB readcorrelations
```

```
GOSUB outputRms
```

```
GOSUB outputRmsmean
```

```
GOSUB outputSkewness
```

```
GOSUB outputKurtosis
```

```
INPUT "press return to quit";a$
```

```
IF nofile = 0 THEN CLOSE #2
```

```
END
```

```
outfile:
```

```
outf$ = title$+":run_"+runNo$+":run_"+runNo$+".correlations"
```

```
OPEN outf$ FOR OUTPUT AS #2
```

```
nofile = 0 'boolean variable used to determine whether or not
to save to disk
```

```
RETURN
```

```
inputTitle:
```

```
'subprogram to input data
```

```
PRINT "What is the disk title?";
```

```
INPUT title$
```

```
PRINT " Run # = ? ";
```

```
INPUT runNo$
```

RETURN

readcorrelations:

subDir\$(1) = "avg Freq Data"

subDir\$(2) = "sigma Data"

subDir\$(3) = "skewness Data"

subDir\$(4) = "kurtosis Data"

FOR j% = 2 TO 5

 f\$ = "trident 2:" + subDir\$(j%-1) + ":run_" + runNo\$ + ".cor"

 PRINT "filename = ", f\$

 OPEN f\$ FOR INPUT AS #1

 FOR i% = 1 TO j%

 INPUT #1, label\$ 'read variable descriptor

 INPUT #1, a\$ 'read value

 IF nofile = 0 THEN

 PRINT #2, label\$

 PRINT #2, a\$

 END IF

 a = VAL(a\$)

 PRINT "value of a =", a

 SELECT CASE j%

 CASE 2

 mean(i%) = a

 CASE 3

 variance(i%) = a

 CASE 4

 cubic(i%) = a

 CASE 5

 kurt(i%) = a

 END SELECT

NEXT i%

CLOSE #1

 IF nofile = 0 THEN PRINT #2, CHR\$(13) 'Blank line

NEXT j%

RETURN

```

outputRms:
FOR i% = 1 TO 3
  SELECT CASE i%
    CASE 1
      type$="xx"
    CASE 2
      type$ ="yy"
    CASE 3
      type$ = "xy"
  END SELECT
  IF variance(i%) < 0 THEN
    rms(i%) = SQR(-1*variance(i%))
  ELSE
    rms(i%) = SQR(variance(i%))
  END IF
  PRINT "RMS";type$;" =",rms(i%)
  IF nofile = 0 THEN 'save
    PRINT #2, "RMS";type$
    PRINT #2, rms(i%)
  END IF
NEXT i%
PRINT
IF nofile = 0 THEN PRINT #2,CHR$(13) 'Blank line
RETURN

```

```

outputRmsmean:
PRINT "RMSxx/MeanX = ",rms(1)/mean(1)
IF nofile = 0 THEN 'save
  PRINT #2, "RMSxx/MeanX"
  PRINT #2, rms(1)/mean(1)
END IF
FOR i% = 1 TO 3
  SELECT CASE i%
    CASE 1
      type$="xx"
    CASE 2

```

```

        type$ ="yy"
    CASE 3
        type$ = "xy"
    END SELECT
    PRINT "RMS";type$;"/MeanY =",rms(i%)/mean(2)
    IF nofile = 0 THEN 'save
        PRINT #2, "RMS";type$;"/MeanY "
        PRINT #2, rms(i%)/mean(2)
    END IF
NEXT i%
IF nofile = 0 THEN PRINT #2,CHR$(13) 'Blank line
PRINT
RETURN

outputSkewness:
FOR i% = 1 TO 4
    numerator = cubic(i%)
    denomX = (SQR(variance(1)))^(4-i%)
    - denomY = (SQR(variance(2)))^(i%-1)
    SELECT CASE i%
        CASE 1
            type$="xxx"
        CASE 2
            type$ ="xxy"
        CASE 3
            type$ = "xyy"
        CASE 4
            type$ = "yyy"
    END SELECT
    skw = numerator/(denomX*denomY)
    PRINT "S";type$;" =",skw
    IF nofile = 0 THEN 'save
        PRINT #2, "S";type$
        PRINT #2, skw
    END IF
NEXT i%

```

```

IF nofile = 0 THEN PRINT #2,CHR$(13) 'Blank line
PRINT
RETURN

```

```

outputKurtosis:

```

```

FOR i% = 1 TO 5

```

```

    numerator = kurt(i%)

```

```

    denomX = (SQR(variance(1)))^(5-i%)

```

```

    denomY = (SQR(variance(2)))^(i%-1)

```

```

    SELECT CASE i%

```

```

        CASE 1

```

```

            type$="xxxx"

```

```

        CASE 2

```

```

            type$="xxxy"

```

```

        CASE 3

```

```

            type$ = "xyyy"

```

```

        CASE 4

```

```

            type$ = "xyyy"

```

```

        CASE 5

```

```

            type$ = "yyyy"

```

```

    END SELECT

```

```

    krt = numerator/(denomX*denomY)

```

```

    PRINT "K";type$;" =",krt

```

```

    IF nofile = 0 THEN 'save

```

```

        PRINT #2, "K";type$

```

```

        PRINT #2, krt

```

```

    END IF

```

```

NEXT i%

```

```

RETURN

```

MEAN VELOCITY CORRELATIONS

REM Program mean velocity correlations

REM This program computes a linear square fit for a, b

REM which are the time averages of the velocity correlations

xMean, yMean

'Note: other 3 programs to calculate velocity correlations using
the 2nd, 3rd, and 4th

'moments are identical to this one except that the functions of
Kx and Ky are

'slightly more complex, the sums created in defineMatrix are
'different but follow the least linear squares theory,

'and the G-J routine has to reduce larger matrices. But since
that flexibility

'has already been built into the basic structure of the program,
they have not been

'documented with as much detail.

'Define variables and constants for equations

' theta = array of angles at which Doppler shifts are found

' DopplerFreq = array of time averaged Doppler shifts of
scattered spectra

' b = 2D array for linear regression matrix

' c = array for linear regression answers

' fminus and fsum = frequencies (in Hz) of the difference and
sum frequencies

' 1482 = speed of sound (in m/s) in water

' kfactor = constant removed from b array to speed up
calculations

DEFDBL B-c

DIM theta(100), B(3,3), c(3),DopplerFreq(100)

LET pi = 3.1415927#

LET lastRow% = 2

LET lastCol% = 2

LET fminus = 93665&

```

LET fsum = 4107553&
LET factor = fminus/fsum
LET kfactor = fsum/ 1482 '1482 m/s = speed of sound in water

```

```

*****

```

```

'Functions

```

```

'   these functions create the theoretical curves that the
Doppler shifts follow

```

```

DEF FNConvertRadian#(x) = x * pi/ 180

```

```

DEF FNKx#(rad) = -(1 - SQR(2)/2*COS(rad) - factor * SIN(rad))

```

```

DEF FNKy#(rad) = -(-SQR(2)/2*SIN(rad) - factor *
SQR(2)/2*COS(rad))

```

```

*****

```

```

'Main program

```

```

'   Loads the data into memory

```

```

'   sets b & c matrices to zero

```

```

'   Defines the linear regression Matrix as groups of sums

```

```

'   Prints the unsolved matrices

```

```

'   Uses Gauss-Jordan row reduction to solve matrix

```

```

'   Prints the solve matrix

```

```

'   Prints the velocity solutions

```

```

'   Creates a data file to compare regression values to actual
data

```

```

GOSUB loadSigma

```

```

FOR i = 1 TO lastRow%

```

```

  FOR J = 1 TO lastCol%

```

```

    LET B(i, J) = 0

```

```

  NEXT J

```

```

  LET c(i) = 0

```

```

NEXT i

```

```

GOSUB defineMatrix

```

```

GOSUB printMatrix

```

```

CALL gaussReduc (lastRow%, B(), c())

```

```

GOSUB printMatrix

```

```

GOSUB outputAnswer

```

```
GOSUB errorAnalysis
END
```

```
*****
```

```
'sub program to input data from files
'  program assumes that zenith analyzed the data and created
'  the file under subdirectory "RUN_#" and file name
"RUN_#.avg"
'  where the # is a number 1-14
'  Variables affected:
'    theta(), DopplerFreq() have proper values for the run#
'    N = number of angles for that run
loadSigma:
PRINT "What is the disk title?";
INPUT title$
PRINT "  Run # = ? ";
INPUT runNo$
f$= title$+":RUN_"+runNo$+":RUN_"+runNo$+".avg"
PRINT "filename = ";f$
OPEN f$ FOR INPUT AS #1
k=0
'Note: each line of data looks like
'  angle <tab> doppler shift <CR>
'  so the parser routine below simply finds the <tab> = chr$(9)
'  and throws the left half in a$, and the right half in b$
WHILE NOT EOF(1)
  INPUT #1,a$
  i%= 0
  done = 0
  WHILE (i% < LEN (a$)) AND (done = 0)
    i% = i%+1
    IF MID$(a$, i%,1) = CHR$(9) THEN done = 1
  WEND
  a= VAL(LEFT$(a$,i%))
  B$= RIGHT$(a$, LEN(a$)-i%)
  B = VAL(B$)
```

```

IF (LEN(a$) <> 0) THEN
    theta(k) = a
    DopplerFreq(k) = B - fsum
    k=k + 1
END IF
WEND
CLOSE #1
N = k - 1
RETURN

```

```

*****

```

```

'sub program to output the mean velocities after the gauss-
'Jordan reduction of the matrix is complete
'Since G-J only explicitly solves for the last variable, the
'program uses the lastRow to solve for the variable above it.
Then it
'cascades upward using solutions that have already been found
to
'get the next
'Also before printing a kfactor is removed from the solution,
this factor was
'removed from the original matrix B to avoid having the
computer create overflow
'errors.
'Variable affected
'    c() = velocity correlations upon exit

```

```

outputAnswer:
coeff$(1) ="xMean"
coeff$(2) ="yMean"
PRINT"From gaussian reduction the solution to matrix equation
is"
c(lastRow%) = c(lastRow%)/ B(lastCol%, lastRow%)
FOR row = (lastRow% -1) TO 1 STEP -1
    sum = 0
    FOR col = row+1 TO lastCol%

```

```

        sum = sum + B(row, col)*c(col)
    NEXT col
    c(row) = c(row) - sum
NEXT row
FOR row = 1 TO lastRow%
    PRINT"      ____"
    c(row) = c(row) / (kfactor)
    PRINT"coefficient ";coeff$(row);" = ";c(row)
NEXT row
PRINT
'This last section allows the user to save the calculated
'veLOCITY information to a text file along with a label -Coeff$(
'for each velocity
'file format is:
'name of velocity correlation <CR>
'value of velocity correlation <CR>
' ...repeat for all velocities
PRINT "Do you want to save to disk?"
INPUT"";ans$
IF NOT LEFT$(ans$, 1) ="n" THEN
    PRINT "Default saves to DISK = trident 2"
    PRINT "  SubDirectory = Avg Freq Data"
    PRINT "  filename = run_";runNo$;".cor"
    PRINT
    PRINT "Do you want to use the default save? ";
    INPUT"";default$
ELSE
    GOTO endOutputAnswer
END IF
IF LEFT$(default$,1) ="n" THEN
    f$ = FILE$(0)
ELSE
    f$ = "trident 2:Avg Freq Data:run_";runNo$+".cor"
END IF
OPEN f$ FOR OUTPUT AS #1
FOR i = 1 TO lastRow%

```

```

PRINT #1, coeff$(i)
PRINT #1, c(i)
NEXT i
CLOSE #1
endOutputAnswer:
RETURN

```

defineMatrix:

'sub program to initialize the b & c matrices
 'Each element of b & c are defined by a sum of function values
 from
 'the linear least squared fit theory.
 'This routine sets up the appropriate functions and sums them
 over
 'all N data points for the run.
 'Variables affected

b(), and c() which are set to initial values

FOR loop = 1 TO N

angle = FNConvertRadian#(theta(loop))

c(1) = c(1) + FNKx#(angle)*DopplerFreq(loop)

c(2) = c(2) + FNKy#(angle)*DopplerFreq(loop)

B(1,1) = B(1,1) + FNKx#(angle)* FNKx#(angle)

B(1,2) = B(1,2) + FNKx#(angle)* FNKy#(angle)

B(2,2) = B(2,2) + FNKy#(angle)* FNKy#(angle)

NEXT loop

'Note: b is a symmetric matrix, thus values repeat in the matrix.

'To avoid having the computer calculate the sum again these
 values are simply

'transcribed after the sum is calculated once.

B(2,1) = B(1,2)

RETURN

printMatrix:

```

'sub program to output the current values of the matrix B
'The matrix is output for debugging purposes and to insure
'the validity of the G-J reduction
'Variables affected
'   none
FOR row = 1 TO lastRow%
  FOR col = 1 TO lastCol%
    PRINT B(row, col);"  ";
  NEXT col
  PRINT c(row)
NEXT row
PRINT
RETURN

```

```

SUB switch(x%, y%, B(2), c(1), last%) STATIC

```

```

*****

```

```

'sub program to interchange rows x, y
'if a zero were to occur in the matrix during the G-J reduction,
'it could cause a division by zero error. This routine switches
out such
'a row for a non-zero one.
'Variables affected
'   b(), c() which have 2 rows interchanged
FOR col = 1 TO last%
  q# = B(x%, col)
  B(x%, col) = B(y%, col)
  B(y%, col) = q#
NEXT col
q# = c(x%)
c(x%) = c(y%)
c(y%) = q#
END SUB

```

```

errorAnalysis:

```

```

*****

```

```

'This program calculates the best fitted values from the

```

```

'computed velocity correlations. It then saves the best fit
values and
'the actual data to a text file so the user can examine the
accuracy of the fit.
'Data file has the form
'* {Data headings} <CR>
'angle at which data taken <TAB> Regression value <TAB> Actual
data <CR>
'....repeated for all N data points
fout$ =title$+":RuN_" +runNo$+":errorA"
OPEN fout$ FOR OUTPUT AS #3
'Make data headings for Cricket graph
'Data headings start with a *
PRINT #3, "*"
outst$ ="theta star"+CHR$(9)+"Regression Plot"+CHR$(9)+"Actual
Data"
PRINT #3, outst$
'Since kfactor has been removed from the fitted constants, it
must be factored
'back in.
FOR loop% = 1 TO N
    angle = FNConvertRadian(theta(loop%))
    f = +c(1) *FNKx#(angle) + c(2) * FNKy#(angle)
    f = f*kfactor
    q = DopplerFreq(loop%)
    outst$ = STR$(theta(loop%))+CHR$(9) +
STR$(f)+CHR$(9)+STR$(q)
    PRINT #3,outst$
NEXT loop%
PRINT
CLOSE #3
RETURN

```

```

SUB findZero (topRow%, B(2), c(1), errors$, lastRow%) STATIC

```

```

'*****

```

'sub program that checks for zeroes in the lead row
 'calls switch if necessary to avoid division by zero errors.
 'Variables affected
 ' errors\$ is a boolean string
 ' = 'false' if no zeros found or the row was replaceable
 ' = 'true' if could not replace row which occurs if the matrix
 ' is nonsingular (i.e. no unique solution)
 ' b(), and c() could have 2 rows interchanged

```
col% = topRow%
errors$= "false"
WHILE (B(topRow%, col%) = 0) AND ( errors$ = 'false")
  row% = topRow% + 1
  check$ ="working"
  'the lead row had a zero, so now we must look through the
  remaining rows to find
  'an non-zero lead row to replace it with.
  WHILE check$ = "working"
    IF (B(row%, col%) = 0) THEN row% = row% + 1 ELSE check$ =
    "done"
    IF row% > lastRow% THEN check$ = "done"
  WEND
  IF NOT row% > lastRow% THEN
    switch row%, topRow%, B(), c(), lastRow%
  ELSE
    errors$= "true"
  END IF
WEND
END SUB
```

SUB gaussReduc (N%,B(2), c(1)) STATIC

'sub program to perform G-J reduction upon a NxN matrix
 'and its solution vector
 'Note: in this case, B is 2 dimensional but the algorithm works

```

'for any square matrix
'Procedure: make first column a 1 and zeros
'           then move to second column, second row and do the
same,
           cascading downwards
'Variables affected:
'   b() is half diagonal
'   c() is manipulated to allow b() to be half diagonal
'   nonsing$ is used to talk between findZero and gaussReduc
to
           detect nonsingular matrices.
FOR row = 1 TO (N%-1)
    leftCol% = row 'use leftRow simply for readability
    findZero leftCol%, B(), c(), nonsing$, N%
    IF nonsing$="true" THEN breakOut
    invers# = 1/ B(row , leftCol%)
    B(row, leftCol%) = 1
    FOR col = leftCol%+1 TO N%
        B(row , col) = B(row , col) *invers#
    NEXT col
    c(row) = c(row) * invers#
    FOR nextRow = row+1 TO N%
        multiplier# = -1*B(nextRow, leftCol%)
        FOR col = leftCol% TO N%
            B(nextRow, col) = B(nextRow, col) + B(row, col)*multiplier#
        NEXT col
        c(nextRow) = c(nextRow) + c(row) * multiplier#
    NEXT nextRow
NEXT row
breakOut:
IF nonsing$ = "true" THEN PRINT "Oh NO!! nonsingular matrix
cannot row reduce!!!!"
END SUB

```

ROTATOR PROGRAM

```

1  REM *****
2  REM ROTATOR.2.MAC FOR IQ400
4  REM MODIFIED 09APR92:
6  REM LINES 1-100 RESET AND RECONFIGURE ALL SIGNALS C. FROM A
    APPLE IIe
10 REM ALPHA# CONTAINS SPECIAL KEYSTROKES FOR IQ400
12 REM MEMORY LOCATIONS -16269 TO -16296 ARE DEDICATED TO THE ROTATOR
    IATOR SWITCHES 0-3. PEEKING THE EVEN VALUES TURNS THEM OFF,
    . ODD TURNS THEM ON.
14 REM LINES 46-64 SET UP SCAN LOOPS AND TIMING FOR STEPPER MOTOR.

38 DIM ALPHA$(26): GOSUB 8900: REM 8900 - INITIALIZE ALPHA#
42 A = PEEK (-16290):A = PEEK (-16292):A = PEEK (-16294):A = PEEK
    (-16296)
44 GOSUB 8500: REM GET INITIAL DATA
46 HOME
48 A$ = "number of 7LS sweeps per angle ":LB$ = "": GOSUB 7000:NS = VAL
    (MM$)
50 GOSUB 8200: REM GET INITIAL,FINAL, AND ANGULAR INCREMENT.
52 NA = INT ((AF - AI) / AD):NA = NA + 1
54 PRINT "number of angles= ";NA
56 ST = (1 / 4) * (4 / 6) * (600) * (200): PRINT ST:"steps= 1 deg on x-be
    am apparatus ":ST = ST * AD
58 PRINT "Number of steps to increment ";AD;" degrees = ";ST
60 MS = INT (ST): PRINT "integer value for number of steps= ";MS
62 AC = MS * AD / ST: PRINT "corresponding to actual increment angle(deg)
    = ";AC
64 M1 = INT (MS / 65536):M2 = INT ((MS - M1 * 65536) / 256):M3 = MS - M
    1 * 65536 - M2 * 256
66 GOSUB 8300: REM GET DATA TITLE
68 GOSUB 15000: REM DECIDE WHETHER OR NOT TO SAVE TRIGGER RAMP
70 GOSUB 8000: REM INPUT PULSE LENGTH
72 GOSUB 10200: REM PRINT ACTUAL MICROPULSE LENGTH
74 D$ = CHR$ (4)
76 Z$ = CHR$ (26)
78 I$ = CHR$ (32 + 1)
80 J$ = CHR$ (32 + 32 + 1)
95 REM *****
96 REM LINES 100-540 REPEATED FOR EVERY ANGLE SCANNED
97 REM . DELAY LOOPS ARE TO ALLOW IQ400 TIME TO EXECUTE COMMANDS BEFORE
    APPLE SENDS ANOTHER COMMAND. WITHOUT THE DELAYS. THE PROGRAM
    AM WILL CRASH'
98 REM 1300 - TURNS ON IEEE 1600 - TURNS OFF IEEE
    "WT" - COMMAND TO IEEE "RD" - IEEE OUTPUT TO
    APPLE
99 REM *****
100 FOR Q = 1 TO NA STEP 1
105 AN = AI + (Q - 1) * AD
107 GOSUB 3000: REM CREATE IQ400 MACROS
108 REM LINES 110-175 RE-ZERO IQ400 ARRAYS BETWEEN ANGLES
110 GOSUB 1300
140 PRINT "WT";I$;Z$;A1$
150 PRINT "WT";I$;Z$;B1$
160 PRINT "WT";I$;Z$;A2$
170 PRINT "WT";I$;Z$;B2$
175 GOSUB 1600
178 REM

```

```

179 REM LINES 180 - 330 REPEATED FOR EVERY 7LS SCAN 124
180 FOR K = 1 TO NS STEP 1
182 REM LINES 185 - 230 COORDINATE TRIGGERS BETWEEN THE 7LS AN
D 10400
185 GOSUB 1300
190 PRINT "WT";I$;Z$;"R"
195 GOSUB 1600
200 GOSUB 4000
210 REM time delay=55sec
220 FOR J = 1 TO 39000 STEP 1: NEXT J
225 GOSUB 1300
227 PRINT "WT";I$;Z$;"S": REM HIT THE HOLD BUTTON TO KILL TRIGGER
228 GOSUB 1600
229 REM delay=2 sec
230 FOR J = 1 TO 5000 STEP 1: NEXT J
235 REM LINES 240 - 260 SIGNAL AVERAGE THE 2 10400 ARRAYS
240 GOSUB 1300
242 PRINT "WT";I$;Z$;A3$
244 GOSUB 1600
246 REM delay=3sec
248 FOR J = 1 TO 8000 STEP 1: NEXT J
250 IF NOADD = 1 THEN 290: REM IF YOU DO NOT WANT TO AVERAGE THE TR
IGGER RAMPs THEN SKIP
252 GOSUB 1300
254 PRINT "WT";I$;Z$;B3$
256 GOSUB 1600
258 REM delay=3sec
260 FOR J = 1 TO 8000 STEP 1: NEXT J
290 PRINT "10400 LOOP=";K
300 PRINT "APPLE IIe LOOP=";G
310 PRINT "SCATTERING ANGLE=";ANG
320 NEXT K
332 REM LINES 335 - 460 SAVES THE AVERAGED SPECTRA TO DISK
335 GOSUB 1300
340 PRINT "WT";I$;Z$;A4$
345 GOSUB 1600
350 REM delay=1sec
360 FOR J = 1 TO 2600 STEP 1: NEXT J
365 GOSUB 1300
370 PRINT "WT";I$;Z$;B4$
375 GOSUB 1600
380 REM delay=1sec
390 FOR J = 1 TO 2600 STEP 1: NEXT J
395 GOSUB 1300
400 PRINT "WT";I$;Z$;C1$
402 GOSUB 1600
405 FOR J = 1 TO 2000: NEXT J
430 FOR J = 1 TO 2000 STEP 1: NEXT J
435 GOSUB 1300
440 PRINT "WT";I$;Z$;A5$
445 GOSUB 1600
450 REM delay=4sec
460 FOR J = 1 TO 15000 STEP 1: NEXT J
461 GOSUB 5000: REM HARD RESET SENT TO 10400. NECESSARY TO REGAIN
CONTROL AFTER DISK USE
480 REM delay=4sec
490 FOR J = 1 TO 15000 STEP 1: NEXT J
500 REM a space to later print out display
510 REM a space to put in an 80sec delay loop
520 IF D ( (NA) THEN GOSUB 6000: REM 6000 - ADVANCES STEPPER MOTOR

```

```

      TO NEXT ANGLE
540  NEXT 0
900  GOSUB 5000
910  END
1290 REM *****
1295 REM 1300 SUBROUTINE TURNS ON IEEE CARD
1297 REM *****
1300 PRINT D$;"PR#7"
1310 PRINT D$;"IN#7"
1320 PRINT "SC1"
1330 PRINT "RA"
1340 RETURN
1490 REM *****
1495 REM 1500 SUBROUTINE RESETS APPLE PERIPHERALS
1497 REM *****
1500 PRINT D$;"IN#0"
1510 PRINT D$;"PR#0"
1520 RETURN
1590 REM *****
1595 REM 1600 SUBROUTINE TURNS OFF IEEE CARD
1597 REM *****
1600 PRINT "UT"
1620 PRINT D$;"IN#0"
1630 PRINT D$;"PR#0"
1640 RETURN
2990 REM *****
2995 REM 3000 SUBROUTINE SETS UP I0400 MACROS
2997 REM *****
3000 REM strings of ASCII code to
3010 REM remote control the I0400
3020 A1$ = "^KAGAI"
3030 B1$ = ""KCGCI"
3040 A2$ = "AB0=AIAI"
3050 B2$ = "AB0=CICI"
3060 A3$ = "A0AGAI"
3070 B3$ = "A0CGCICI"
3080 A4$ = "ACAI" + STR$ (NS) + "=AI"
3090 B4$ = "ACCI" + STR$ (NS) + "=CI"
3100 G2$ = STR$ (AN)
3102 G1$ = "K"
3104 G3$ = "M00"
3106 C1$ = G1$ + G2$ + G3$
3110 A5$ = "_AAC" + NAM$ + "M00AAI"
3130 C3$ = "_AAC" + NAM$ + "M00EC01="
3140 C4$ = "_DAE"
3150 RETURN
3990 REM *****
3995 REM 4000 SUBROUTINE TURNS ANNUNCIATOR 1 ON & OFF TO TRIGGE
      R 7LS'S SWEEP
4000 REM *****
4010 A = PEEK ( - 16293)
4020 FOR J = 1 TO 50: NEXT J
4030 A = PEEK ( - 16294)
4040 RETURN
4990 REM *****
4995 REM 5000 SUBROUTINE TURNS ANNUNCIATOR 2 ON & OFF TO SEND A HARD R
      ESET TO I0400
5000 REM *****
5010 A = PEEK ( - 16291)
5020 FOR J = 1 TO 50: NEXT J
5030 A = PEEK ( - 16292)
5035 FOR J = 1 TO 4000: NEXT J
5040 RETURN

```

```

5995 REM 6000 SUBROUTINE EXECUTES A MACHINE LANGUAGE
E TO ACTIVATE STEPPER MOTOR
6000 REM SUBROUTINE IS CALLED:
6010 REM MSK.FEB1991.STEPPER
6020 REM PULSER PROGRAM
6030 REM FOR USE W/ MOTOR 100 ON 1500 OFF
6040 REM SLO-SYNC STEP MOTOR WORKED
6050 REM WELL @ 50MICROSEC"ON" AND 1500MICROSEC"OFF"
6060 REM INPUT # MICROSECONDS ON
6070 REM INPUT # MICROSECONDS OFF
6080 REM NUMBER OF BURSTS=
6090 REM STEPS ARE LIMITED TO 256+(256)*(256)
6100 REM DATE:FEB 2, 1991
6110 REM USE ANNOUNCE OR PORT #0 FOR PULSES
6120 REM THIS IS A MODIFICATION OF THE
6130 REM PULSE BURST SEQUENCE program
6140 REM PROGRAMMERS = MURRAY KORMAN & CHRISTINA BURCH
6145 REM *****
6150 GOSUB 10000: REM GET J AND K (LENGTH OF PULSES)
6200 R = M2:S = M2
6310 FOR I = 864 TO 891
6320 READ A
6330 POKE I,A
6340 NEXT I
6345 RESTORE
6350 IF R = 0 THEN GOTO 6410
6360 POKE 865,I
6370 POKE 867,R
6380 POKE 873,G
6390 POKE 881,H
6400 CALL 864
6410 PRINT "GET READY"
6420 PRINT "MICROSECONDS ON = ";K
6430 PRINT "MICROSECONDS OFF = ";J
6440 PRINT "READY"
6450 PRINT "GO..."
6460 IF S = 0 THEN GOTO 6540
6470 POKE 867,255
6480 POKE 865,S
6490 POKE 867,255
6500 POKE 873,G
6510 POKE 881,H
6520 CALL 864
6540 IF M1 = 0 THEN 6620
6550 POKE 867,255
6560 POKE 865,255
6570 POKE 867,255
6580 POKE 873,G
6590 POKE 881,H
6600 CALL 864
6610 M1 = M1 - 1: GOTO 6540
6620 FOR W = 1 TO 5: CALL -198: NEXT W
6630 PRINT D$: REM BECAUSE OF CALL -198
6640 RETURN
6990 REM *****
6995 REM 7000 SUBROUTINE OUTPUTS STRINGS TO PRINTER. NECESSARY BECAUS
E PRINTER CARD TURNED ON & OFF QUITE FREQUENTLY.
7000 REM *****
7010 PRINT " Enter 'A$' ('LB$:')": INPUT MM$

```

```

7020 NN$ = LEFT$ (A$,1): REM ALTERNATE ENTRY POINT FOR OTHER ROUTINES.
7030 NN$ = CHR$ (ASC (NN$) - 32)
7040 A$ = NN$ + RIGHT$ (A$, LEN (A$) - 1)
7050 REM LINES 7020-7040 CAPITALIZE THE FIRST LETTER OF A$
7060 PRINT CHR$ (4);"PR#1"
7070 PRINT " ";A$;" = ";MM$;" ";LB$
7080 PRINT CHR$ (4);"PR#0"
7090 RETURN
7095 REM *****
7097 REM 7100 SUBROUTINE OUTPUTS SIMPLE STRINGS TO PRINTER
7100 REM *****
7110 PRINT CHR$ (4);"PR#1"
7120 PRINT A$
7130 PRINT CHR$ (4);"PR#0"
7140 RETURN
7190 REM *****
7195 REM 7200 SUBROUTINE OUTPUT BLANK LINE TO PRINTER
7200 REM CHR$(10) IS A LINE FEED CHARACTER
7205 REM *****
7210 A$ = CHR$ (10)
7220 GOSUB 7100
7230 RETURN
7290 REM *****
7295 REM 7300 SUBROUTINE SETS UP OUTPUT FOR PRINTER IF TWO OUTPUT
S ARE NEEDED.
7300 REM *****
7310 PRINT " ";A1$;"(";"LB$;")";: INPUT N1$
7320 PRINT " ";A2$;"(";"LB$;")";: INPUT N2$
7330 A$ = " " + A1$;MM$ = N1$: GOSUB 7060: REM USING ALTERNATE ENTRY
POINT
7340 A$ = " " + A2$;MM$ = N2$: GOSUB 7060: REM USING ALTERNATE ENTRY
POINT
7350 RETURN
7390 REM *****
7395 REM 7400 SUBROUTINE SETS UP OUTPUT FOR CHOICES
7400 REM *****
7410 PRINT " Enter ";A$;" (";"CH$;")";: INPUT MM$
7420 NN$ = LEFT$ (A$,1)
7430 NN$ = CHR$ (ASC (NN$) - 32)
7440 A$ = NN$ + RIGHT$ (A$, LEN (A$) - 1)
7450 REM LINES 7020-7040 CAPITALIZE THE FIRST LETTER OF A$
7460 PRINT CHR$ (4);"PR#1"
7470 PRINT " ";A$;" = ";MM$
7480 PRINT CHR$ (4);"PR#0"
7490 RETURN
8000 REM *****
8005 REM 8000 SUBROUTINE INPUTS PULSE SPEEDS FOR ROTATION STEPPER
MOTOR.
8010 REM *****
8020 PRINT : PRINT "default settings": PRINT " for the pulse duration, a
nd pulse repetition period of the electronic pulse to the s
tepper motor.": PRINT " 200 microseconds on.": PRINT " 6000 microseconds off
8030 PRINT : INPUT " Is this acceptable (y/n)? Note: this

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will be the last prompt before the experiment commences. ";DFT$
8040 IF LEFT$ (DFT$,1) = "N" OR LEFT$ (DFT$,1) = "n" THEN 8060
8050 O = 200:P = 6000: GOTO 8080
8060 INPUT "How long should the pulse be on (microsec)? Note 200 should
be the minimum. ";O
8070 INPUT "How long should the pulse be off? Note: 6000 should be min-
imum. ";P
8080 RETURN
8190 REM *****
8195 REM 8200 SUBROUTINE GETS 3 IMPORTANT PARAMETERS AI -
INITIAL ANGLE OF SCAN AF - FINAL ANGLE OF SCAN AD - A-
NGULAR INCREMENT BETWEEN SCANS
8200 REM *****
8210 A$ = "initial angle":LB$ = "deg": GOSUB 7000:AI = VAL (MM$)
8220 A$ = "final angle":LB$ = "deg": GOSUB 7000:AF = VAL (MM$)
8230 A$ = "increment angle":LB$ = "deg": GOSUB 7000:AD = VAL (MM$)
8240 RETURN
8290 REM *****
8295 REM 8300 SUBROUTINE INPUTS A FILENAME TO SAVE THE DATA U-
NDER.
8297 LINES 8320 - 8390 ON VERTHEFI LEN AME TO ASTRINGTHEID400CANUSE.
8300 REM *****
8305 NAM$ = ""
8310 PRINT : INPUT "Enter a 5 character code to save the data under..
.";TITLE$
8315 IF LEN (TITLE$) > 5 THEN PRINT "ERROR!! The maximum length of a
data label is 5 characters. ": GOTO 8305
8317 IF LEN (TITLE$) < 1 THEN PRINT "ERROR!! You must type something!
!": GOTO 8305
8320 FOR J = 1 TO LEN (TITLE$)
8330 CHAR$ = MID$ (TITLE$,J,1): REM GET A CHARACTER OFF OF STRING
8340 IF (ASC (CHAR$) > 96) AND (ASC (CHAR$) < 123) THEN CHAR$ = CHR$
(ASC (CHAR$) - 32): REM MAKES LOWER CASE INTO UPPER CASE
8350 IF (ASC (CHAR$) > 64) AND (ASC (CHAR$) < 91) THEN NCHAR$ = ALPHA$
(ASC (CHAR$) - 64): GOTO 8380: REM IF LETTER THEN DECODE
8360 IF (ASC (CHAR$) > 47) AND (ASC (CHAR$) < 58) THEN NCHAR$ = CHAR$:
GOTO 8380: REM A NUMBER HAS BEEN CHOSEN
8370 PRINT : PRINT "ERROR!! You can only enter alphanumeric characters."
: GOTO 8305
8380 NAM$ = NAM$ + NCHAR$
8390 NEXT J
8392 A$ = "Data file name...":MM$ = TITLE$:LB$ = "": GOSUB 7060
8395 RETURN
8430 REM *****
8495 REM 8500 SUBROUTINE GETS TIME AND DATE OF SCAN. THEN ASKS I-
F USER WANTS TO INPUT ALL PARAMETERS OF THE SCAN
8500 REM *****
8510 INPUT "Enter date (JUN-02-1992) ";DT$
8520 INPUT "Enter time (HHMM) ";TM$
8525 PRINT CHR$ (4):"PR#1"
8530 PRINT "Date: ";DT$: PRINT "Time: ";TM$
8535 PRINT CHR$ (4):"PR#0"
8540 INPUT "Do you wish to enter the settings for the 7LS spectrum ana-
lyzer and the LeCroy?";ANS: IF LEFT$ (ANS,1) = "Y" THEN GOSUB
8600
8550 RETURN
8590 REM *****
8595 REM 8600 SUBROUTINE GETS SETTINGS OF MONITORING EQUIPM-
ENT OF THE APPARATUS
8600 REM *****
8610 GOSUB 7200:A$ = "7LS Spectrum Analyzer Settings": GOSUB 7100
8620 A$ = "horizontal scale":LB$ = "kHz/div": GOSUB 7000

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8630 A$ = "resolution":LB$ = "Hz": GOSUB 7000
8640 A$ = "position of dot marker":LB$ = "kHz": GOSUB 7000
8650 A$ = "vertical scale":LB$ = "microvolts/div": GOSUB 7000
8660 GOSUB 7200:A$ = "10400 settings:": GOSUB 7100
8670 A$ = "block size":LB$ = "bytes": GOSUB 7000
8680 A$ = "sample interval":LB$ = "ms": GOSUB 7000
8690 A$ = "Enter the vertical range settings": GOSUB 7100:A1$ = "Channel
e1 A":A2$ = "Channel B":LB$ = "+/- v": GOSUB 7300
8710 A$ = "Enter the method of coupling - DC/AC": GOSUB 7100:A1$ = "Channel A":A2$ = "Channel B":LB$ = "": GOSUB 7300
8720 A$ = "Enter the bias": GOSUB 7100:A1$ = "Channel 1":A2$ = "Channel
1 B":LB$ = "": GOSUB 7300
8750 A$ = "trigger source":LB$ = "": GOSUB 7000
8760 A$ = "slope":CH$ = "+/-": GOSUB 7400
8770 A$ = "trigger coupling":CH$ = "AC/DC": GOSUB 7400
8780 A$ = "level":LB$ = "%": GOSUB 7000
8790 A$ = "window":LB$ = "%": GOSUB 7000
8795 A$ = "delay":LB$ = "": GOSUB 7000
8800 GOSUB 7200:A$ = "Miscellaneous items:": GOSUB 7100
8805 A$ = "water pressure":LB$ = "psi": GOSUB 7000
8810 A$ = "Enter peak-peak voltages on transducers 1 and 2.": GOSUB 71
00:A1$ = "Transducer 1":A2$ = "Transducer 2":LB$ = "v": GOSUB 7300
8820 A$ = "depth of water":LB$ = "cm": GOSUB 7000
8830 A$ = "voltage attenuation":LB$ = "(20dB)": GOSUB 7000
8840 A$ = "translation":LB$ = "in.": GOSUB 7000
8850 A$ = "direction of translation":LB$ = "Right/Left": GOSUB 7000
8860 GOSUB 7200: HOME : RETURN
8890 REM *****
8895 REM 8900 SUBROUTINE ASSIGNS VALUES TO ALPHA$
8900 REM *****
8902 ALPHA$(1) = "G"
8904 AL$(2) = "B"
8906 AL$(3) = "D"
8908 AL$(4) = "F"
8910 AL$(5) = "H"
8912 AL$(6) = "J"
8914 AL$(7) = "A"
8916 AL$(8) = "C"
8918 AL$(9) = "E"
8920 AL$(10) = "G"
8922 AL$(11) = "I"
8924 AL$(12) = "K"
8926 AL$(13) = "ODN"
8928 AL$(14) = "OBN"
8930 AL$(15) = "ODN"
8932 AL$(16) = "OFN"
8934 AL$(17) = "OHN"
8936 AL$(18) = "OJN"
8938 AL$(19) = "OAN"
8940 AL$(20) = "OCN"
8942 AL$(21) = "OEN"
8944 AL$(22) = "OGN"
8946 AL$(23) = "OIN"
8948 AL$(24) = "OKN"
8950 AL$(25) = "NBO"
8952 AL$(26) = "NEO"
8960 RETURN
8990 REM *****
8995 REM 9000 SUBROUTINE DECIMAL FORM OF MACHINE CODE PART A
UNS STEPPER MOTOR
9000 REM *****

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```

9010 DATA 173,89,192,169,3
9020 DATA 32,168,252,173,88
9030 DATA 192,169,43,32,168
9040 DATA 252,202,208,236,136
9050 DATA 208,231,96
9990 REM *****
9995 REM 10000 SUBROUTINE CONVERTS INPUTTED PULSE LENGTH INTO A
      N ACTUAL NUMBER THE COMPUTER CAN USE.
9999 REM *****
10000 X = (210.25 - 10 * (13 - 0)) * (1 / 2)
10010 Y = (- 14.5 + X) / 5
10020 Z = (- 14.5 - X) / 5
10030 IF Y > Z THEN G = Y
10040 IF Z > Y THEN G = Z
10050 G = INT (G)
10060 LET K = 5 * G * G + 27 * G + 26
10070 LET K = K / 2
10080 C = (210.25 - 10 * (13 - P)) * (1 / 2)
10090 D = (- 14.5 + C) / 5
10100 E = (- 14.5 - C) / 5
10110 IF D > E THEN H = D
10120 IF E > D THEN H = E
10130 H = INT (H)
10140 LET J = 5 * H * H + 27 * H + 26
10150 LET J = J / 2
10160 RETURN
10190 REM *****
10195 REM 10200 SUBROUTINE PRINTS OUT THE ACTUAL PULSE LENGTH
      S CALCULATED IN 10000
10200 REM *****
10210 GOSUB 10000
10220 PRINT CHR$(4);"PR#1"
10230 PRINT "Pulse on for ";K;" microseconds"
10240 PRINT "Pulse off for ";J;" microseconds"
10250 PRINT CHR$(4);"PR#0"; REM SHUT OFF PRINTER
10260 RETURN
14990 REM *****
14995 REM 15000 SUBROUTINE ALLOWS USER TO DECIDE IF REVERSE WAY E
      TO AVERAGE TRIGGER RAMP-- IF YOU DON'T AVERAGE. PROGRAM RUNS FAS
      ER BY ABOUT 2 HOURS.
14999 REM NOADD IS A BOOLEAN VARIABLE AND EQUALS 1 IF USER CHOOSES
      S NOT TO AVERAGE TRIGGERS
15000 REM *****
15010 NOADD = 1
15020 PRINT "What is the width of the display? (1/4 or 1/2) "; INPUT
      ZX$
15030 IF ZX$ = "1/2" THEN NOADD = 0
15040 RETURN

```

ANALYZER PROGRAM

```

1  REM hi-techniques 1999 transfers 401/42 to Apple IIe. then statistics
   are performed on the array. A loop continues for any number of arrays.
2  PRINT "ANALYZER PROGRAM" : GOTO 10000
3  DIM F$(150): DIM R$(150)
4  DIM I(1030)
5  DIM G(1030), H(1030), J(1030), K(1030), L(1030), M(1030), N(1030), O(1030), P(1030), Q(1030), R(1030), S(1030), T(1030), U(1030), V(1030), W(1030), X(1030), Y(1030), Z(1030)
   = OF SCAN POSITIONS = 50
6  GOSUB 8000: GOSUB 4000: REM POSITION ALPHABET AND GET INITIAL DATA
7  GOSUB 5000: REM GET P AND C
8  FOR JJ = FIRST TO LAST STEP 1
9  GOSUB 3000
10 D$ = CHR$(4)
11 Z$ = CHR$(26)
12 PRINT D$;"PR#7"
13 PRINT D$;"IN#7"
14 PRINT "SC1"
15 PRINT "RA"
16 PRINT "WT":Z$;"_KCEAS"
17 X = 1
18 PRINT "RDA":Z$:
19 GET B$
20 IF ASC(B$) = 13 THEN GOTO 250
21 IF B$ = "," THEN GOTO 240
22 C$ = C$ + B$
23 GOTO 200
24 PRINT C$:F$(X) = C$
25 X = X + 1
26 C$ = " "
27 IF X = 139 THEN GOTO 270
28 GOTO 190
29 PRINT "UT"
30 PRINT D$;"PR#0"
31 PRINT D$;"IN#0"
32 REM reset 10400 after data transfer.
33 A = PEEK(-16291): FOR I = 1 TO 1000 STEP 1: NEXT I
34 A = PEEK(-16292): FOR I = 1 TO 10000 STEP 1: NEXT I
35 FLASH
36 PRINT "WORKING ON SUBROUTINE 1000"
37 NORMAL
38 GOSUB 1000
39 FLASH
40 PRINT "WORKING ON SUBROUTINE 2000"
41 NORMAL
42 GOSUB 2000
43 NEXT JJ
44 FLASH: PRINT "SAVING DATA TO DISK": NORMAL
45 GOSUB 6000
46 END
47 FOR X = 1 TO 138 STEP 1
48 J = 0
49 IF X >= 6 AND X <= 69 THEN J = X - 5

```

```

1030 IF X = 75 AND X = 135 THEN GOTO 1040
1040 IF J = 0 THEN GOTO 1125
1040 L = 1
1050 K = (8 * J) - (8 - L)
1060 H$ = MID$(F$(X),3,12)
1065 G(K) = VAL(H$)
1070 M = 14
1080 FOR L = 2 TO 8 STEP 1
1090 K = (8 * J) - (8 - L)
1100 H$ = MID$(F$(X),M,11)
1105 G(K) = VAL(H$)
1110 M = M + 11
1120 NEXT L
1125 NEXT X
1130 RETURN
2000 REM STATISTICAL CALCULATIONS
2010 REM IF CONTINUOUS INPUT OF P AND Q NECESSARY GOSUB 5000 HERE
2020 C1 = 18.7: REM C1 AND C2 ARE CALIBRATION FACTORS THAT WERE EXPERIMENTALLY DETERMINED
2030 C2 = 3.622
2040 FOR K = P TO Q STEP 1
2050 I(K) = (C1 * G(K) + C2) / 2
2060 NEXT K
2070 AA = 0: BB = 0
2080 FOR K = P TO Q STEP 1
2090 XX = (1 / 2) * (I(K + 1) + I(K))
2100 AA = AA + XX
2110 BB = BB + XX * K
2120 NEXT K
2130 II(JJ) = AA
2140 FF(JJ) = BB / AA
2150 CC = 0: DD = 0: EE = 0
2160 FOR K = P TO Q STEP 1
2170 XX = (1 / 2) * (I(K + 1) + I(K))
2180 CC = CC + XX * (K - FF(JJ)) / 2
2190 DD = DD + XX * (K - FF(JJ)) / 3
2200 EE = EE + XX * (K - FF(JJ)) / 4
2210 NEXT K
2220 VAR(JJ) = CC / II(JJ)
2230 RMS(JJ) = SQR(VAR(JJ))
2240 SKEW(JJ) = DD / (II(JJ) * (RMS(JJ) / 3))
2250 KURT(JJ) = EE / (II(JJ) * (RMS(JJ) / 4))
2260 PRINT D$:"PR#1"
2265 PRINT "SCAN POS= ";JJ
2270 PRINT "P CURSOR= ";P
2280 PRINT "Q CURSOR= ";Q
2285 REM XF IS THE VOLTAGE ATTENUATION FACTOR WHICH IS INCLUDED NOW TO COMPUTE INTENSITY
2290 PRINT "INTENSITY= ";II(JJ) / (XF / 2)
2300 PRINT "AVE FREQ= ";FF(JJ)
2310 PRINT "RMS FREQ= ";RMS(JJ)
2320 PRINT "VARIANCE= ";VAR(JJ)
2330 PRINT "SKEWNESS= ";SKEW(JJ)
2340 PRINT "KURTOSIS= ";KURT(JJ)

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```

2340 PRINT
2350 PRINT D$;"PR#0"
2360 RETURN
3000 D$ = CHR$(4)
3010 Z$ = CHR$(26)
3020 PRINT D$;"PR#7"
3030 PRINT D$;"IN#7"
3040 PRINT "SC1"
3050 PRINT "AA"
3060 E1$ = "AAA" + NAM$ + "="
3070 E2$ = "AAG"
3080 A$ = STR$(JJ)
3090 E$ = E1$ + A$ + E2$
3100 PRINT "WT";Z$;E$
3110 FOR I = 1 TO 15000 STEP 1: NEXT I
3115 PRINT "UT"
3116 PRINT D$;"PR#0"
3117 PRINT D$;"IN#0"
3120 A = PEEK(-16291)
3130 FOR I = 1 TO 1000 STEP 1: NEXT I
3140 A = PEEK(-16292)
3150 FOR I = 1 TO 10000 STEP 1: NEXT I
3160 RETURN
4000 REM INITIAL DATA
4010 GOSUB 8300: REM GET TITLE AND KEYSTROKES FOR TITLE
4020 PRINT : PRINT "What is the first scan position";: INPUT FIRST
4030 PRINT : INPUT "What is the last scan position";: LAST
4040 INPUT "Enter voltage attenuation factor in dB ";:XF
4050 PRINT CHR$(4);"PR#1"
4055 INPUT "Enter the angular setting of RALMIKE turntable : ";:B
4060 PRINT "Data from scan positions ";FIRST;" to ";LAST
4065 IF LAST - FIRST > 50 THEN PRINT "ERROR!! This program will only accept 50 scan positions. To input more change the dimensions of the variables on line 6 and this line, 4065.": STOP
4070 PRINT " NOTE: Attenuation factor of ";XF;" d is used throughout calculations."
4071 PRINT " ";XF;" dB translates to a decimal factor of ";:GOSUB 9000: PRINT XF: REM 9000 CONVERTS XF TO DECIMAL VALUE
4075 PRINT " Also, the angular setting of RALMIKE is ";B;" degrees."

4077 PRINT : PRINT
4080 PRINT CHR$(4);"PR#0"
4090 RETURN
5000 REM THIS ROUTINE MINDS ITS P's AND Q's
5005 REM P AND Q MARK THE LEFT AND RIGHT BOUNDARIES TO INTEGRATE EACH RAY
5010 PRINT "SCAN POSITION = ";JJ
5040 PRINT : PRINT "Enter P ";: INPUT P$
5050 PRINT "Enter Q ";: INPUT Q$
5060 IF LEN(P$) = 0 THEN 5040: REM DONT CHANGE P
5070 P = VAL(P$)
5080 IF LEN(Q$) = 0 THEN 5040
5090 Q = VAL(Q$)
5100 IF Q < P THEN PRINT "ERROR!! P needs to mark the left portion of the domain and Q the right.": GOTO 5000
5110 RETURN
6000 REM SAVE DATA TO DISK
6005 IF (ASC(T1$) > 47) AND (ASC(T1$) < 127) THEN PRINT : PRINT "Since 1st character of title is a P. : PRINT T1$
6010 FTITLE$ = TITLE$ + ".INTENSITY"

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```

6030 PRINT D$; "OPEN ";FTITLE$
6032 PRINT D$; "WRITE ";FTITLE$
6035 REM LAST = LAST SCAN POSITION
6037 REM FIRST = FIRST SCAN POSITION
6040 PRINT LAST - FIRST + 1
6050 FOR JJ = FIRST TO LAST STEP 1
6060 PRINT JJ
6070 PRINT II(JJ)
6080 NEXT JJ
6090 PRINT D$; "CLOSE"
6095 PRINT D$; "LOCK ";FTITLE$
6100 FTITLE$ = TITLE$ + ".AVERAGE FREQ"
6120 PRINT D$; "OPEN ";FTITLE$
6130 PRINT D$; "WRITE ";FTITLE$
6140 PRINT (LAST - FIRST) + 1
6150 FOR JJ = FIRST TO LAST STEP 1
6160 PRINT JJ
6170 PRINT FF(JJ)
6180 NEXT JJ
6190 PRINT D$; "CLOSE"
6195 PRINT D$; "LOCK ";FTITLE$
6200 FTITLE$ = TITLE$ + ".RMS FREQ"
6220 PRINT D$; "OPEN ";FTITLE$
6230 PRINT D$; "WRITE ";FTITLE$
6240 PRINT (LAST - FIRST) + 1
6250 FOR JJ = FIRST TO LAST STEP 1
6260 PRINT JJ
6270 PRINT RMS(JJ)
6280 NEXT JJ
6290 PRINT D$; "CLOSE"
6295 PRINT D$; "LOCK ";FTITLE$
6300 FTITLE$ = TITLE$ + ".VARIANCE"
6320 PRINT D$; "OPEN ";FTITLE$
6330 PRINT D$; "WRITE ";FTITLE$
6340 PRINT (LAST - FIRST) + 1
6350 FOR JJ = FIRST TO LAST STEP 1
6360 PRINT JJ
6370 PRINT VAR(JJ)
6380 NEXT JJ
6390 PRINT D$; "CLOSE"
6395 PRINT D$; "LOCK ";FTITLE$
6400 FTITLE$ = TITLE$ + ".SKEWNESS"
6420 PRINT D$; "OPEN ";FTITLE$
6430 PRINT D$; "WRITE ";FTITLE$
6440 PRINT (LAST - FIRST) + 1
6450 FOR JJ = FIRST TO LAST STEP 1
6460 PRINT JJ
6470 PRINT SKEW(JJ)
6480 NEXT JJ
6490 PRINT D$; "CLOSE"
6495 PRINT D$; "LOCK ";FTITLE$
6500 FTITLE$ = TITLE$ + ".KURTOSIS"
6520 PRINT D$; "OPEN ";FTITLE$
6530 PRINT D$; "WRITE ";FTITLE$
6540 PRINT (LAST - FIRST) + 1
6550 FOR JJ = FIRST TO LAST STEP 1
6560 PRINT JJ
6570 PRINT KUR(JJ)
6580 NEXT JJ
6590 PRINT D$; "CLOSE"
6595 PRINT D$; "LOCK ";FTITLE$
6600 RETURN

```

```

8300 REM GET A TITLE FOR DATA
8305 NAM$ = ""
8310 PRINT : INPUT "Enter the title of the file to be read ":TITLE$
8315 IF LEN (TITLE$) > 5 THEN PRINT "ERROR". The maximum length of a
      data label is 5 characters. ": GOTO 8305
8317 IF LEN (TITLE$) < 1 THEN PRINT "ERROR". You must enter something.
      ": GOTO 8305
8320 FOR J = 1 TO LEN (TITLE$)
8330 CHAR$ = MID$ (TITLE$,J,1): REM GET A CHARACTER OFF OF STRING
8340 IF ( ASC (CHAR$) > 96) AND ( ASC (CHAR$) < 123) THEN CHAR$ = CHR$
      ( ASC (CHAR$) - 32): REM MAKES LOWER CASE INTO UPPER CASE
8350 IF ( ASC (CHAR$) > 64) AND ( ASC (CHAR$) < 91) THEN NCHAR$ = ALPHA$
      ( ASC (CHAR$) - 64): GOTO 8380: REM IF LETTER THEN DECODE
8360 IF ( ASC (CHAR$) > 47) AND ( ASC (CHAR$) < 58) THEN NCHAR$ = CHAR$:
      GOTO 8380: REM A NUMBER HAS BEEN CHOSEN
8370 PRINT : PRINT "ERROR". You can only enter alphanumeric characters."
      : GOTO 8305
8380 NAM$ = NAM$ + NCHAR$
8390 NEXT J
8392 PRINT CHR$ (4);"PR#1": PRINT "Data file name...":TITLE$
8394 PRINT CHR$ (4);"PR#2"
8395 RETURN
8900 REM ASSIGN MACROS TO LETTERS
8902 ALPHA$(1) = "A"
8904 AL$(2) = "B"
8906 AL$(3) = "D"
8908 AL$(4) = "F"
8910 AL$(5) = "H"
8912 AL$(6) = "J"
8914 AL$(7) = "A"
8916 AL$(8) = "C"
8918 AL$(9) = "E"
8920 AL$(10) = "G"
8922 AL$(11) = "I"
8924 AL$(12) = "K"
8926 AL$(13) = "ODN"
8928 AL$(14) = "OBN"
8930 AL$(15) = "ODN"
8932 AL$(16) = "OFN"
8934 AL$(17) = "OHN"
8936 AL$(18) = "DJN"
8938 AL$(19) = "OAN"
8940 AL$(20) = "OCN"
8942 AL$(21) = "OEN"
8944 AL$(22) = "OGN"
8946 AL$(23) = "OIN"
8948 AL$(24) = "OKN"
8950 AL$(25) = "NBO"
8952 AL$(26) = "NEO"
8960 RETURN
9000 REM dB TO DECIMAL CONVERTER
9010 XF = - 1 * XF / 20: REM BECAUSE VOLTAGE IS THE SQRT OF POWER
9020 XF = 10 * XF: REM CONVERTS
9030 RETURN

```

MAC ANALYZER PROGRAM

```

{note: no decimals in the angles}
{updated 25Mar92}
program Macintosh_analyzer;

uses
  dos, crt;

const
  maxpts = 40; {equal to max angles any one data run will
have}
                                     {unlikely to be larger
than 20}
  offset = 3.823; {updated 18Mar92 to 25Feb92 calibrations}
  vdiv = 19.8162;
  interval = 0.050; {seconds per point}
  noisefactor = 0.00; {noise contribution per point}
  path = 'a:\';
type
  v_arry = array [1..2000] of real;
  str80 = string[80];
  str40 = string[40];
  str20 = string[20];
  str8 = string[8];
  realArray = array [1..maxpts] of real;
  strAry = array[1..10] of str8;

var
  f : text;
  volt : v_arry;
  NumFiles, i, runs, last_pt, p, q, run_no, dBs : integer;
  x, time, angle, current_angle, actual_angle, dBFactor : real;
  ExperNum, dataname, possibly : str8;
  PtVal, Xavg, Variance, Rms, Skewness, Kurtosis, intensity2,
    time_intens2, thirdmom, fourthmom : realArray;
  nextFile : SearchRec;
  fil : str80;
  fileName, ExperAry : strAry;

procedure getFileInfo;
var
  i : integer;

```

```

begin
  write('Number of files to read? ');
  readln(NumFiles);
  for i := 1 to NumFiles do
    begin
      write('Enter name of file ',i,' ');
      readln(fileName[i]);
      write('Enter Experiment# of file ',i,' ');
      readln(ExperAry[i]);
    end;
  end;

```

```

procedure nextAngle(var A : integer);
var
  s1 : str80;
  error : integer;

begin
  FindNext(nextfile);
  if doserror = 0 then
    begin
      s1 := copy(nextfile.name,6,3);{strip out angle}
      val(s1, A, error);
    end
  else {errors mean last file read}
    a := -99;
  end;

```

```

function convert_angle(theta : integer) : integer;

begin
  theta := theta - 284;
  if theta < -180 then
    theta := theta +360;
  convert_angle := theta;{sets range at -180 to 180}
end;

```

```

procedure getFirstFile(var a : integer);
var
  s2 : str80;

```

```

        s1 : str20;
error : integer;

begin
    s2 := copy(dataname,1,4);{strip 4 characters}
    s2 := concat(s2,ExperNum);
    s2 := concat(path, dataname,('.'#,ExperNum,')\'; s2,'*.asc');
    repeat
        findFirst(s2, anyfile, nextfile);
        if doserror <> 0 then
            begin
                writeln('Check to see if 'path,' has correct
data disk.');
```

```

                writeln('I'm looking for file ',s2);
                repeat until readkey = #13;
                end;
            until doserror = 0;
            s1 := copy(nextfile.name, 6,3);
            val( s1, a, error);
            end;

procedure alternatparser(a1 : str80; var x : real);

var
    error : integer;

begin
    val(a1, x , error);
end;

procedure readwave(filenam : str80);

var
    f : text;
    pt : integer;
    temp_str : str80;

begin
    pt := 0;
    assign(f, filenam);
    reset(f);
    readln(f, temp_str);{first 2 lines are useless to me}
    readln(f, temp_str);

```

```

while not (eof(f) or (pt > 1999)) do
begin
    pt := pt + 1;
    readln(f, temp_str);
    temp_str := copy(temp_str, 5, 100); {strip first 4
characters from
                                temp_str -- ie. " " }
    alternateparser( temp_str , volt[pt]);
end;
close(f);
last_pt := pt;
end;

procedure get_pq;

var
    filenam : str40;
    f : text;
    angle, file_p, file_q : real;

begin
    filenam :=
concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.pq
m');
    assign(f, filenam);
    reset(f);
    repeat
        readln(f,angle, file_p, file_q);
        writeln('angle = ',angle:12:5,' filep = ',file_p:12:5);
    until (trunc(angle) = run_no) or (eof(f));{again this is an
approximation}
        {that works only for half and integer angles}
    close(f);
    if trunc(angle) <> run_no then
        begin
            writeln('Error!! could not find angle ',run_no,' in
.pqm file');
            q := -1;
        end
    else
        begin
            p := round(file_p);
            q := round(file_q);

```

```

        end
    end;

function dB_to_decimal(dB:integer):real;

var
    exponent : real;

begin
    exponent := (-1) * dB / 20 * ln(10);
    dB_to_decimal := exp(exponent);
end;

procedure getdBatten(var attenuation: integer);

var
    filenam : str40;
    f : text;
    angle : real;

begin
    filenam :=
concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.db
x');
    assign(f, filenam);
    reset(f);
    readln(f, attenuation);
    close(f);
    dBFactor := dB_to_decimal(attenuation);
end;

procedure calibrate;

var
    i : integer;

begin
    writeln('starting calibration');
    for i := p to q+1 do
        begin
            volt[i] := vdiv*volt[i]+offset;
            if volt[i] < 0 then

```

```

        begin
            writeln('underflow occurred at pt ',i);
        end;
        volt[i] := volt[i]*volt[i];
    end;
end;

procedure integrate1(var intsum, averval : real);

var
    i : integer;
    xx, firstmom : real;

begin
    writeln('starting integration1');
    intsum := 0;
    firstmom := 0;
    for i := p to q do
        begin
            xx := 1/2 *(volt[i] +volt[i+1]);
            intsum := intsum +xx;
            firstmom := firstmom + xx*i
        end;
    averval := firstmom / intsum
end;

procedure integrate2(intensity, avgval : real;var Variance,
Rms, Sk,
        third, fourth, Kurt : real);

var
    i : integer;
    xx, cc, dd, ee : real;

begin
    writeln('starting integration2');
    cc := 0;
    dd := 0;
    ee := 0;
    for i := p to q do
        begin
            xx := 1/2 *(volt[i] +volt[i+1]);
            cc := cc + xx * sqr(i - avgval);

```

```

        dd := dd + xx * sqr(i - avgval) * (i - avgval);
        ee := ee + xx * sqr ( sqr (i- avgval));
    end;
    variance := cc / intensity;
    rms := sqrt(variance);
    third := dd/intensity;
    fourth := ee / intensity;
    sk := dd / (intensity * rms * rms * rms);
    kurt := ee / (intensity * sqr (sqr (rms)));
    end;

    procedure noise_reduc(var noise : real);

    begin
        noise := (q - p) * noisefactor;
    end;

    procedure savedata(lastposit : integer);

    var
        f : text;
        i : integer;
        filenam : str40;

    begin
        {save average frequency}
        filenam :=
        concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.avg');
        assign(f, filenam);
        rewrite(f);
        for i := 1 to lastposit do
            writeln(f, ptval[i], ' ',Xavg[i]);
        close(f);
        {save variance}
        filenam :=
        concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.var');
        assign(f, filenam);
        rewrite(f);
        for i := 1 to lastposit do
            writeln(f, ptval[i], ' ', Variance[i]);
        close(f);
    end;

```

```

        {save rms frequency}
    filenam :=
concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.r
ms');
    assign(f, filenam);
    rewrite(f);
    for i := 1 to lastposit do
        writeln(f, ptval[i], ' ', Rms[i]);
    close(f);
    {save skewness}
    filenam :=
concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.sk
w');
    assign(f, filenam);
    rewrite(f);
    for i := 1 to lastposit do
        writeln(f, ptval[i], ' ', Skewness[i]);
    close(f);
    {save kurtosis}
    filenam :=
concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.kr
t');
    assign(f, filenam);
    rewrite(f);
    for i := 1 to lastposit do
        writeln(f, ptval[i], ' ', Kurtosis[i]);
    close(f);
    {save intensity}
    filenam :=
concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.i2'
);
    assign(f, filenam);
    rewrite(f);
    for i := 1 to lastposit do
        writeln(f, ptval[i], ' ', intensity2[i]);
    close(f);
    {save third moment}
    filenam :=
concat('b:',dataname,'_',ExperNum,'\',dataname,'_',ExperNum,'.3r
d');
    assign(f, filenam);
    rewrite(f);
    for i := 1 to lastposit do

```

```

        writeln(f, ptval[i], ' ', thirdmom[i]);
        close(f);
        {save fourth moment}
        filename :=
concat('b:', dataname, '_', ExperNum, '\', dataname, '_', ExperNum, '.4t
h');
        assign(f, filename);
        rewrite(f);
        for i := 1 to lastposit do
            writeln(f, ptval[i], ' ', fourthmom[i]);
        close(f);
        end;

procedure define_intensity(integral : real; var intensity2, time2
: real);
    var
        xx, timeintvl : real;

    begin {two methods are used to calculate intensity because
I'm not sure
        where noise is }
        noise_reduc(xx);
        intensity2 := (integral / (dBFactor * dBFactor)) - xx;
        timeintvl := (q - p) * interval; {converts points to time
domain}
        time2 := intensity2 * timeintvl;
        end;

(*main program*)
begin
    writeln('Don't forget to update noiselevel in the constant
section!!!');
    write('Stop???');
    readln(possibly);
    if upcase(possibly[1]) = 'Y' then exit;
    getFileInfo;
    for runs := 1 to NumFiles do
        begin
            dataname := fileName[runs];
            ExperNum := ExperAry[runs];
            getFirstFile(run_no);
            getDBAtten(dBs);

```

```

if dBs = -100 then {error occurred}
    run_no := -100; {and stop}
i := 0;
while run_no >= 0 do
    begin
        fil := concat(path,dataname,'(.#',ExperNum,')\ ', nextfile.name);
        readwave(fil);
        get_pq;
        calibrate;
        i := i + 1;
        integrate1(x, Xavg[i]);
        integrate2(x, Xavg[i], Variance[i], Rms[i], Skewness[i],
thirdmom[i], fourthmom[i], Kurtosis[i]);
        define_intensity(x,intensity2[i],time_intens2[i]);
        ptval[i] := convert_angle(run_no);
        writeln('At angular position ',ptval[i]);
        writeln('The runNumber is ',run_no);
        writeln('The result of integration is ',x:12:5);
        writeln('Intensity information:');
        writeln(' Integral * dB');
        writeln(' Intensity          = ',intensity2[i]:12:5);
        writeln('    w/ time interval    = ',time_intens2[i]:12:5);
        writeln('The average frequency = ',Xavg[i]:12:5);
        writeln('The variance          = ',Variance[i]:12:5);
        writeln('The Rms frequency      = ',Rms[i]:12:5);
        writeln('The Skewness          = ',Skewness[i]:12:5);
        writeln('The Kurtosis          = ',Kurtosis[i]:12:5);
        writeln('The Third moment      = ',thirdmom[i]:12:5);
        writeln('The Fourth moment     = ',fourthmom[i]:12:5);
        writeln;
        writeln('Note: intensity and average frequency values are
subject to');
        writeln('other calibrations that have not been included in the
current');
        writeln('calculations. ');
        writeln;
        NextAngle(run_no);
    end;
    if run_no <> -100 then {might have problem with dbx file}
        savedata(i);
    end; {for runs}
end.

```